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Averaging and summation of influences on visually perceived eye level between two long lines differing in pitch or roll-tilt

Leonard Matin *, Wenxun Li

Clarence H. Graham Memorial Laboratory of Visual Science, Department of Psychology, Columbia University, New York, NY 10027, USA

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Abstract

The presence of one or two long, dim, eccentrically-placed, parallel, pitched-from-vertical lines in darkness generates a systematic influence on the physical elevation that appears to correspond to eye level (VPEL). The influence of the line(s) in darkness is nearly as large as that produced by a complexly-structured, well-illuminated visual field (Matin L, Li W. Vis Res, 1994;34:311–330); oblique lines in a frontoparallel plane that strike the same projected orientations generate the same influences as those generated by pitched-from-vertical lines (Li W, Matin L. Perception, 1996;25:831–852). The two experiments described here examined the influence on the physical elevation of VPEL due to simultaneous viewing of two long lines of different pitch (Experiment 1) or two long lines of different obliquity in a frontoparallel plane (Experiment 2). Experiment 1 employed two long (66°), simultaneously-presented, pitched-from-vertical lines in darkness on bilaterally symmetric locations at 25° horizontal eccentricity, with each line at one of seven pitches in the range from $-30°$ to $+30°$; VPELs were measured for all 49 possible pitch combinations. Experiment 2 was identically constructed, but employed oblique 2-line stimuli from a frontoparallel plane that struck the same projected orientations as did the pitched-from-vertical lines in Experiment 1. VPELs measured on four subjects in the two experiments were indistinguishable for corresponding conditions of pitch and obliquity. For a given pitch (obliquity) of one of the lines the elevation of VPEL increased linearly with the pitch (obliquity) of the second line. The VPEL for any 2-line combination is very close to the average of the VPELs for the two individual lines; a small amount of additive summation between the influences of the two lines was also found. Parallel and nonparallel 2-line stimuli appear to follow the same rules of combination. The results are clear in showing that the visual influence on VPEL is controlled by an opponent-process mechanism.

Keywords: Visually perceived eye level; Space perception; Spatial orientation; Spatial localization; Disorientation; Perception of elevation

1. Introduction

The three-dimensional space of our everyday experience normally appears as a stable framework within which objects in the world can be localized. It appears to extend in front of us along directions above, below, to the left, and to the right of our bodies and to be an unchanging medium whereas the objects within it show us different faces as we and they move about. However, the characteristics of perceived space are shaped by our nervous systems as are the perceptual properties of objects, and, although there are other important influences such as those that derive from the orientation of the eyes in the head, the head on the neck, and the orientation and magnitude of the gravitoinertial vector (Matin, 1972, 1983, 1986; Lackner, 1978; Cohen, 1981), under most conditions the most significant contributor to this shaping of perceived space is visual stimulation itself. These visual influences are carried by some of the very same visual objects whose perceived locations and orientations are themselves determined by the significant characteristics of the perceived space which they influence. This reciprocal relation of space and object within perception is reminiscent of the reciprocal influences between physical space and matter. But our interest here is only in perception, and within perception, only in the influence of stationary visual stimulation on one of the dimensions of the egocentric perception of space, the perception of elevation.

A number of significant consequences of this pervasive influence of visual stimulation on the visual percep-

* Corresponding author. E-mail: matin@columbia.edu.

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tion of space have been studied previously. Some of these are consequences of properties inherent in stationary visual fields such as the influence on the orientation of the perceived vertical within an observer's frontoparallel plane that is generated by a visual field tilted within the frontoparallel plane (Gibson, 1937; Asch and Witkin, 1948; Witkin and Asch, 1948; Witkin, 1949; Bischof, 1974; Ebenholtz, 1977; Purcell, Wenderoth and Moore, 1978; Howard, 1982; Mittelstaedt, 1986, 1988). Others result from visual motion such as the misattribution of visual motion by an observer to motion of the observer's own body and/or to bodily tilt (Dichgans and Brandt, 1972; Dichgans, Held, Young and Brandt, 1972; Brandt, Dichgans and Koenig, 1973; Held, Dichgans and Bauer, 1975; Leibowitz, Post, Brandt and Dichgans, 1982).

The orientation of either a stationary or a moving visual field significantly influences the perception of elevation. Whereas the influences measured by Witkin and Asch (Asch and Witkin, 1948; Witkin and Asch, 1948; Witkin, 1949; Bischof, 1974) were generated by rolled visual fields, and the influences from visual motion were from either roll or yaw (Dichgans and Brandt, 1972; Dichgans, Held, Young and Brandt, 1972; Brandt, Dichgans and Koenig, 1973; Held, Dichgans and Bauer, 1975; Leibowitz, Post, Brandt and Dichgans, 1982), the influence on the perception of elevation is most readily generated by a pitched visual field (Matin and Fox, 1989). And again, as in the above examples, unusual pitches of the visual field result in marked changes in a number of significant features of an observer's perceptions of space and in sensorimotor behavior in addition to the influence on the visual perception of elevation. We have referred to this complex as the Spatial Disorientation Syndrome Produced by Visual Pitch. The main features of this complex include significant modifications in the correspondence between visually perceived elevation and manual settings of elevation to physical elevation, changed perceptions of the size and height of objects within the visual field, changes in the orientation perceived as vertical within a sagittal plane, and mislocalization by the subject in attempts to set the eye to a given direction of gaze (Matin and Fox, 1989; Li and Matin, 1990, 1991, 1995, 1996a, 1998; Stoper and Cohen, 1989; Stoper and Bautista, 1991; Matin and Li, 1992a,b, 1994a,b,c, 1995a,b; Nemire and Cohen, 1993; Cohen, Ebenholtz and Linder, 1995; Servos, Matin and Goodale, 1995; Robison, Li and Matin, 1995; Chelette, Li, Esken and Matin, 1995; Post and Welch, 1996; Welch and Post, 1996; DiZio, Li, Lackner and Matin, 1997).

The elevation of a visual target set by the observer to appear at eye level (VPEL) has been particularly useful in assessing these influences, for a shift of this single measure is part of an essentially rigid shift in the perceived elevation of at least a very large portion of the visual field, and very likely the entire field. The relation of the value of VPEL to pitch approximates a linear relation over the range that has been examined from 40° topbackward ($-40°$) to 30° topforward—with topbackward pitch generating lower VPELs and topforward pitch generating elevated values; for both, deviations of VPEL from its dark value increase with the magnitude of the pitch. The slope of the VPEL-versus-pitch function has averaged between $+0.33$ and $+0.63$, a value that depends on several parameters of the visual field and on the particular individuals in the group of observers. Although the slope of the linear function varies considerably among individuals, the settings made by a given individual have remained fairly stable for periods that have so far extended over as much as 10 years. With a complexly-structured, well-illuminated visual field, the range of slopes across different subjects has extended from a low of $+0.14$ to a high of $+0.86$. No differences have been measured between subjects viewing monocularly and binocularly (Matin and Fox, 1989; Stoper and Cohen, 1989; Matin and Li, 1992a).

A major portion of the influence of visual pitch on VPEL can be generated by the pitched-from-vertical line segments in the field with monocularly-viewing subjects. For example, a long (64°), single, pitched-from-vertical line in otherwise total darkness generates an influence that is only 16% less than the influence generated by the complexly-structured, well-illuminated visual field, and the influence generated by two such parallel, bilaterally symmetric lines falls between that of the complex visual field and that of the single line (Matin and Li, 1992a, 1994a). The influence of the pitch of the plane containing a single line[1] at 25° eccentricity grows exponentially with line length with a space constant of about 15°, and the influence of two bilaterally symmetric short lines is very nearly equal to the influence of a single line with the same total length (Matin and Li, 1994b). Horizontal lines in the surface facing the observer exert a small influence at most (Matin and Li, 1992a), an influence that appears to be essentially, if not entirely, accounted for by variation of the height of the line in the field (Li and Matin, 1990).

2. Nodal planes and the projection sphere

The influence on VPEL from individual lines is not limited to straight pitched-from-vertical lines from pitched-only planes. An influence of equal magnitude is measured when the observer views a visual field consist-

[1] Since a single line belongs to an infinite number of planes, referring to a line as possessing pitch is inaccurate. However, we will sometimes do so in order to avoid lengthier statements; there should be no ambiguity in the present context.

ing of a single straight oblique, line in the same nodal plane (Fig. 1) as the pitched-from-vertical line (Li and Matin, 1996a). This identity of influence on VPEL for lines (and/or curves) arising from different planes (and/ or surfaces) of origin provides one of the bases for shifting our focus from stimulus lines in object space to their images. The projection sphere[2] in Fig. 2 permits a representation of the orientation of a line in terms of the nodal plane to which it belongs independently of the depth or orientation of the plane of origin of the line (or for that matter, of its shape); all lines (straight or curved) in a given nodal plane are designated by the common orientation of the great circle containing their images on the sphere. Our interest in the present article will be in straight pitched-from-vertical lines in pitched-only planes and those lines from a frontoparallel plane that lie in the same nodal planes. As described in the legend to Fig. 2, the spheres are centered on the nodal point of the eye of an observer in primary viewing position. Panels (a), (c), (e), and (g) each display two pitched-from-vertical lines imaged via central projection through a pinhole at the center of the sphere on to great circles on the sphere's rear surface; panels (b), (d), (f), and (h) show identical image locations on the projection sphere to those in (a), (c), (e), and (g) respectively, that result from stimulation by oblique stimulus lines on an erect plane. These four pairs of panels in Fig. 2 display examples of the main cases of stimulation by a 2-line pitched-from-vertical visual field along with their oblique counterparts that are examined in the present experiments. The pitched-from-vertical 2-line pairs are the parallel pitched-from-vertical pair in (a), the equal-and-opposite-pitch pair in (c), and the pitched-from-vertical pairs whose members differ in magnitude and/or direction in (e) and (g).

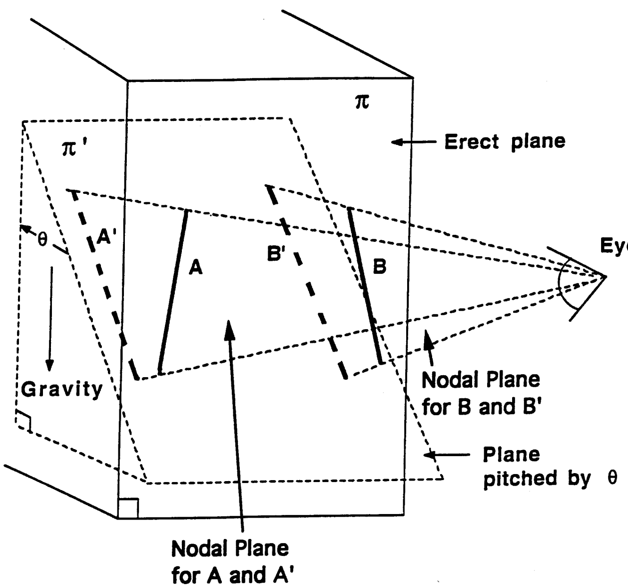

Fig. 1. Two parallel pitched-from-vertical lines, A' and B' (dark dashed lines), lie on pitched-only plane π'; two oblique lines, A and B (dark solid lines), lie on erect plane π frontoparallel to the observer. The normal line (not shown) of visual direction to the erect plane falls halfway between lines A and B on π and halfway between A' and B' on π'. A and B are central projections of A' and B' on the eye, respectively. Each of the two nodal planes passes through the nodal point of the eye.

[2] Although specification of location on the spherical surface only requires two numbers, the relations among three make it easy to relate the characterization to concepts normally employed in visual science. Thus, for a great circle, where μ_i, μ_j, and μ_k are the intersections on the CVM, CMFP, and equator, respectively (Fig. 2), $\tan \mu_i = \tan \mu_j / \tan \mu_k$, and a given intersection point of the great circle containing the image of a line on the CVM corresponds to a given pitch or equivalent pitch, an intersection point on the equator to a given eccentricity relative to the median plane, and an intersection point on the CMFP corresponds to a given obliquity within an erect plane or its equivalent in a pitched plane. Since the tangent relation above indicates that together with a single point on the CVM another on the equator specifies a unique great circle, the great circles that intersect a fixed point on the equator and a succession of equidistant points on the half of the CVM that is visible in the panels of Fig. 2, correspond to lines at a single eccentricity from a set of planes at equally spaced pitches.

Although the lack of dependence of VPEL on the plane of origin of a stimulus line found in the work we have carried out previously is a significant reason for focusing on the nodal plane and thus on the projection sphere, four empirical lines of work have led us in the same direction: (1) The details of retinal stimulation from a line, aside from the projected orientation and eccentricity, do not appear to influence the VPEL discrimination. Thus, neither cues accompanying accommodation of the lens in the eye nor retinal gradients of line width, luminous intensity, and line spread accompanying variation in the distance of different parts of a line play any significant role in generating the influences on VPEL (Matin and Li, 1992a, 1994a; Post and Welch, 1996). (2) VPEL values resulting from the viewing of pitched-from-vertical lines in pitched-only planes or oblique lines in frontoparallel planes indicate that, although a pitched-from-vertical line extends in depth relative to the observer, information regarding this variable depth is not a significant basis for the VPEL discrimination with monocular viewing by the stationary observer (Matin and Li, 1992a, 1994a; Li and Matin, 1996a). In addition, VPEL values obtained with monocular and binocular viewing of the complexly-structured pitchroom are indistinguishable (Matin and Fox, 1989; Matin and Li, 1992a), as are VPEL measurements with a smaller visual field (Stoper and Cohen, 1989). (3) For the erect observer VPEL remains essentially unchanged with changes in either the vertical or horizontal orientation of the eye in the head and/or the head relative to physical space (Li and Matin, 1991, 1993; Matin and Li, 1995a). Thus, although we originally introduced the projection sphere in the context of experiments for which it was useful to treat it as a

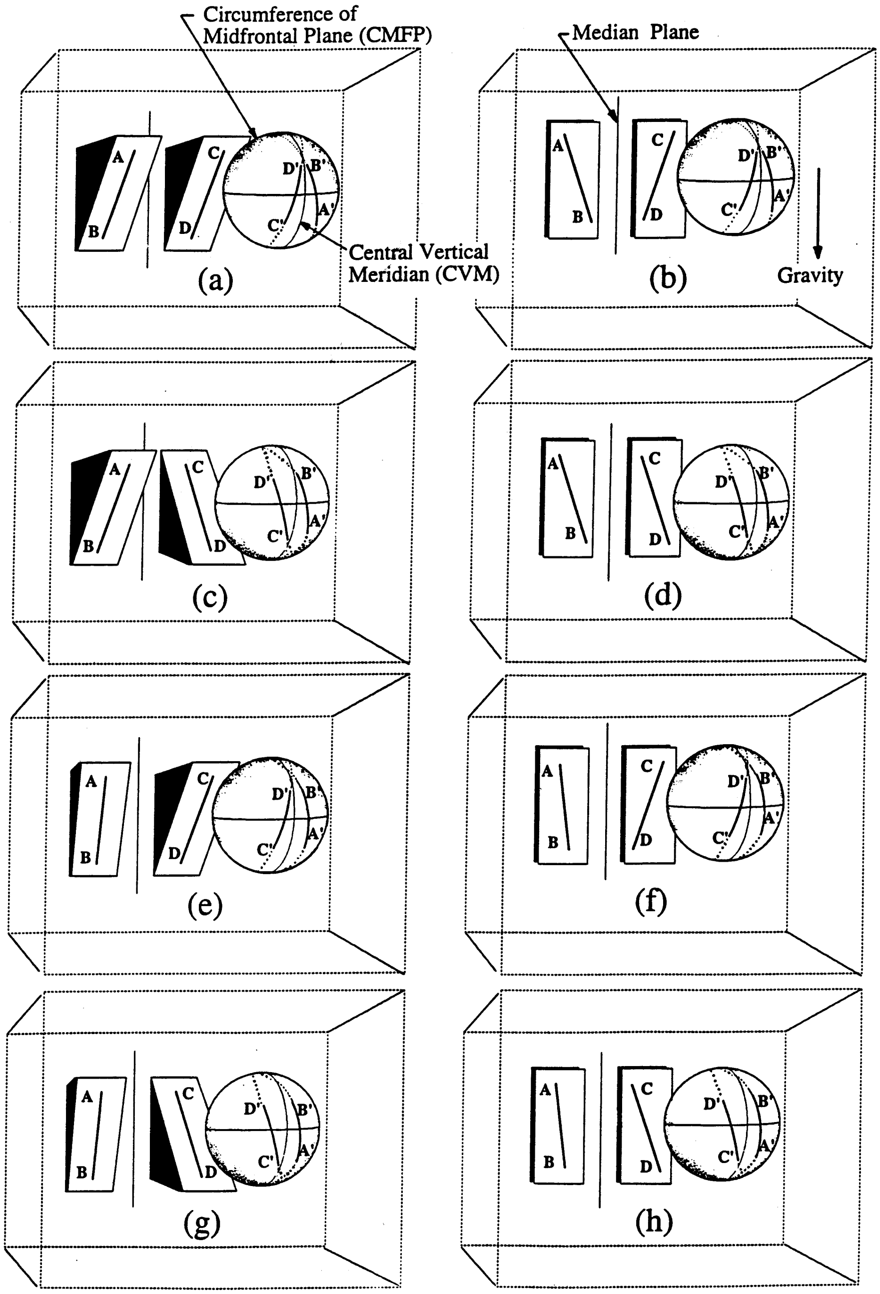

Fig. 2. Sketches of a projection sphere centered at the nodal point of the eye of an erect subject viewing a 2-line visual field in primary position. The central vertical meridian (CVM) is the great circle that corresponds to the median plane of the observer; the circumference of the midfrontal plane (CMFP) is a frontoparallel section through the sphere; the equator is horizontal at the observer's eye level. In each panel the two lines are at equal horizontal eccentricities on opposite sides of the median plane. Each of the four pairs of panels ((a)/(b), (c)/(d), (e)/(f), (g)/(h)) displays the identity of central projections on the projection sphere from two pitched-from-vertical lines on pitched-only plane(s) with two oblique lines on an erect frontoparallel plane. The four pairs are examples of the four cases examined in the present experiments. The two lines in (a) are parallel and lie in a single pitched-only plane whereas the two lines in its erect-plane counterpart in (b) are mirror symmetrical; the two lines in (c) lie in pitched-only planes of equal and opposite pitch whereas the two lines in its erect-plane counterpart in (d) are parallel. The two lines arise from planes and pitched by different amounts in the same direction in (e) and by different amounts in opposite directions (g); their counterparts in the erect plane in (f) and (h) are tilted from erect by different amounts in opposite directions and different amounts in the same direction, respectively.

spherical approximation to the stationary eye of the observer (with no implication regarding quantitative similarity between the shapes of the sphere and the eye), these results require that we treat the orientation of the projection sphere as fixed in space around an eye and erect head whose orientation relative to the erect, stationary body in space is free to vary. (4) Change in the height within the visual field of pitched-from-vertical lines does not influence the slope of the VPEL-versus-pitch function although it does add a constant to each of the VPEL values (Li and Matin, 1990).

3. The present experiments

The earlier experiments employed parallel 2-line stimuli. Although some work was done with 2-line stimuli of equal and opposite pitch, previous work had not yet dealt with the general case for line pairs that were not parallel. The present experiments employ pairs of such long lines, both pitched-from-vertical lines and lines of equivalent pitch in the frontoparallel plane. Measurements were also made on parallel, pitched-from-vertical, 2-line pairs involving the same individual lines as those in the nonparallel pairs and their counterparts of equivalent pitch; these include some of the conditions previously reported and provide a bridge to the previous experiments. The experiments in the present article were followed by an essentially identical experiment with short pitched-from-vertical 2-line stimuli (Li and Matin, 1996b) and another set with 3-line stimuli (Li and Matin, 1997); these experiments will be fully described in two additional reports. The reliability of VPEL measurements is sufficiently great (Matin and Li, 1994a) so that, although conducted at an earlier date, results from experiments with 1-line stimuli under identical conditions and with the same subjects as are employed in the present experiments will be brought to bear on our analysis below without further replication here. Together, the results from these earlier experiments along with those from these latter sets of experiments provide a picture of the rules of combination for influences on VPEL from individual lines. In a fourth article we develop a theoretical treatment that makes use of orientation-selective neural units and accounts quantitatively for the response to the individual line as well as the two- and three-line combinations described in the present article and the two to follow.

4. Method

4.1. General

Two experiments were conducted. In each, the erect, monocularly-viewing subject, with head stabilized by a chinrest, viewed a visual field consisting of two lines ('2-line stimulus') in otherwise total darkness. The two lines were presented at 25° horizontal eccentricity with one line on each of the two opposite sides of the median plane. In each condition the subject set the elevation of a small dim target to appear at eye level (VPEL setting) while viewing the 2-line stimulus. The two lines were presented at one of a number of different orientations. In Experiment 1 the lines were pitched-from-vertical (i.e. the plane containing a line was pitched-only; with the plane erect and frontoparallel, the line was vertical). The axis of rotation for pitch was a horizontal line in the plane of the stimulus at the true eye level of the subject. In Experiment 2 the lines originated from an erect frontoparallel plane; their rool-tilt within the erect plane was systematically varied and values were chosen so that the orientation and location of the image on the projection sphere matched the projected orientation of one of the pitched-from-vertical conditions. In both experiments viewing distance was maintained at 1 m in all conditions. The 1 m distance was measured along the normal line of visual direction within the midsagittal plane from the eye to the surfaces containing the lines; these surfaces were perpendicular to the midsagittal plane under all conditions. To maintain this viewing distance the physical distance from the subject to the axis of the pitchable surfaces containing the lines were changed along with changes in pitch[3].

4.1.1. Experiment 1: pitched-from-vertical 2-line stimuli

VPEL measurements were made while the monocularly-viewing subject viewed a 2-line, pitched-from-vertical stimulus with the left line at one of seven pitches in combination with one of the same seven pitches of the right line. Measurements were made with all 49 possible combinations of pitch of the two lines. The seven pitches employed were $\pm 30°$, $\pm 20°$, $\pm 10°$, and 0° (erect). The negative sign for pitch refers to an orientation in which the line was pitched topbackward (i.e. the top of the line was rotated away from the subject); topforward pitch is designated by a positive sign (+) or no designation. In a single session only one pitch of

[3] Fixing viewing distance along the normal at 1 m and employing an axis of rotation at true eye level, as in the present experiments, maintained the elevation of the center of the lines at a fixed height. But it produced some variation in horizontal eccentricity of the lines measured on the equator of the projection sphere: The eccentricities of the lines measured at the equator for the different pitch settings employed were as follows: 0° pitch, eccentricity: 25°; $\pm 10°$ pitch, eccentricity: 24.67°; $\pm 20°$ pitch, eccentricity: 23.66°; $\pm 30°$ pitch, eccentricity: 21.99°. Fixing the height of the visual field results in smaller slopes for the VPEL-versus-pitch function (as in the present experiments and in those in Li and Matin, 1995, 1996a than allowing the height of the visual field to change with pitch as it does in our pitchroom as in Matin and Fox, 1989; Matin and Li, 1994a,b). The basis for at least a major portion of this difference, if not the entire difference, is a consequence of a 10% change in bias of the entire VPEL-vs-pitch function produced by the height change, an affect separable from and additive to the influence of pitch (Li and Matin, 1990). The increasing positive height bias that co-occurs with increasing topforward pitch and increasing negative height bias that co-occurs with increasing topbackward pitch results in larger VPEL values at the more topforward pitches and more negative VPEL values at the more topbackward pitches, resulting in larger slopes than those measured where height is fixed as in Fig. 5.

the right line was employed in combination with all seven pitches of the left line. The order of presentation of the seven left-line pitches was randomized separately within a session for each of the four subjects as was the order of pitches of the right line among sessions. Thus, the full experiment occupied seven sessions for each subject.

4.1.2. Experiment 2: oblique 2-line stimuli

VPEL measurements were made while the subject viewed the left line at each of seven orientations within the frontoparallel plane in combination with one of the same seven orientations of the right line. Measurements were made with all 49 possible combinations of orientations of the two lines. Each of the obliquities (roll-tilts) of each line was chosen to yield stimulation to the right eye of the monocularly-viewing subject for which the retinal location and size was identical to the corresponding pitched-from-vertical line (Fig. 1). We thus refer to the obliquity of a line as measured by its equivalent pitch as well as by its physical orientation within the stimulus plane. Eq. (1) provides the transform between visual pitch, θ, of a plane that contains a pitched-from vertical line at a horizontal eccentricity measured on the normal plane, μ, and the obliquity, ρ, of a line within a frontal plane, that possesses the equivalent pitch to that of the pitched-from-vertical line (see Appendix in Li and Matin, (1996a) for derivation and details):

$$\rho = \arctan [\tan \mu \times \sin \theta] \quad (1)$$

The roll-tilts of the lines of equivalent pitch in the frontoparallel planes were ± 4.3; ± 9.1; and ± 13.2; these corresponded to pitches of ± 10; ± 20; and $\pm 30°$, respectively.

There was one difference in procedure between Experiments 1 and 2: Whereas in Experiment 1 the pitch of the right line was fixed in each session and the pitch of the left line was varied within a session, in Experiment 2 the obliquity of the left line was fixed in each session and the obliquity of the right line was varied within a session. Thus, in a single session only one obliquity of the left line was employed in combination with the seven obliquities of the right line. The order of presentation of the seven right-line obliquities was randomized separately within a session for each of the four subjects as was the order of the obliquities of the left line among sessions. Thus, the full experiment occupied seven sessions for each subject.

There were two differences between the retinal stimulation produced by the oblique lines in the erect plane employed in Experiment 2 and the pitched-from-vertical lines in the pitched-only planes in Experiment 1. (1) Whereas the normal line of visual direction to the pitched-from-vertical line from the viewing eye declines with increasing topbackward pitch or with decreasing topforward pitch, it rises with equivalent pitch changes in obliquity of the lines on the erect plane that correspond to the real pitch changes. Since the normal line of visual direction intersects the stimulus line at a distance from the eye that is the shortest for any point on the stimulus line, the gradient of geometric width of the retinal image of the line is broadest at this intersection with the normal. Since the normal undergoes oppositely-directed changes in elevation with real pitch and with the corresponding equivalent pitch, so too do the centers of these width gradients. (2) The individual pitched-from-vertical line has different depth gradients for different pitches; these are larger than the comparable depth gradients for the oblique lines in the erect plane which stimulate identical retinal orientations. Our previous work has demonstrated that the conjunction of both of these differences plays no role in the cases previously explored (1-line and 2-line parallel, pitched-from-vertical stimuli and their counterparts from the frontoparallel plane (Matin and Li, 1992a, 1994a; Li and Matin, 1996a). One facet of the present experiments explores the possibility that this conclusion holds for all combinations of line orientation.

4.2. Stimulus display

Each line consisted of a strip of phosphorescent tape that had received a brief exposure (~ 2 min) to normal room illumination prior to each experimental run; this was refreshed for approximately 30–60 s following each set of four VPEL measurements. Each of the two strips was 144 cm $\times$ 0.2 cm with a luminance of approximately 0.01 ml (EG&G photometer/radiometer 550). Each strip was attached to one of two plastic bars which was mounted on a modified standalone, rotatable blackboard (154 $\times$ 104 cm) by attachment with velcro at the top and bottom. The two plastic bars could be independently moved upward or downward, rightward or leftward, or rolled to the right or left. Thus, the strips of phosphorescent tape could produce various visual patterns. The two strips were symmetrically placed with respect to the midsagittal plane of the subject's viewing eye at horizontal eccentricities of 25° measured at normal; horizontal separation between the two lines was thus 50°. As measured between the subject's eye and the erect blackboard each of the two luminous strips subtended a 66° $\times$ 6 minarc visual angle at the viewing distance of 1 m.

In Experiment 1, where the pitches of the two lines had to be set separately, two separate pitchable blackboards were employed. In Experiment 2, where the two lines were both in a frontoparallel plane, both were mounted on one blackboard. In Experiment 2 a vertical slot, 1 cm wide, that was cut in the middle of the blackboard, was covered by a strip of translucent white plastic cloth attached to the surface on the side of the board that faced away from the subject. An optically attenuated beam from a 0.5 mw He-Ne laser, mounted on a vertical track via a rack and pinion arrangement attached to a mobile relay rack in the back of the blackboard, was projected on to the rear surface of the cloth and was visible to the subject as a 20 minarc circular red target at the 1 m viewing distance that was employed in the experiments. The beam was projected horizontally and was itself invisible. The experimenter was able to adjust the elevation of the laser-generated target by moving it along the vertical track and locking it into place. For Experiment 1, the vertical slot was cut in a separate board that was mounted on a vertically-standing relay rack between the two pitchable blackboards. Since pitching the two lines in Experiment 1 and roll-tilting them in Experiment 2 would have produced differences in projected length at the eye and some differences in projected height of the lines, both of these were corrected in Experiment 2 by adjustments that involved height changes of the physical line stimuli and appropriate covering of their ends to equalize projected length in comparable conditions in the two experiments.

4.3. Procedure

The same general procedure was followed in both experiments. The subject straddled a stool facing the modified, rotatable blackboard(s) with head position stabilized by a chinrest attached to the back of the stool. The display was viewed with the right eye; the left eye was occluded by an eye patch. The visual field was completely dark with the exception of the lines and the laser target described above. A method of adjustment with hunting was employed for the setting of the laser target to VPEL by the subject. A trial began with the subject's eye closed and the experimenter set the laser target either far above or far below the region of uncertainty and instructed the subject to open his/her eyes, fixate the target, and report whether the target needed to be moved up or down in order to appear at VPEL; the subject immediately closed his/her eyes, whereupon the experimenter reset the elevation of the target by a variable amount and instructed the subject to open his/her eyes again and report on the elevation of the target relative to VPEL again. This sequence was repeated until the subject indicated that the target was at VPEL. Four such settings were made before proceeding to another combination of pitches (Experiment 1) or of equivalent pitches (Experiment 2). Two of each set of four trials began with the target's initial position far above the region containing the VPEL, two began below; the four were sequenced in abba order.

In each session a series of four trials was run in total darkness prior to the seven 2-line conditions, and a second 4-trial series in total darkness was run following the seven 2-line conditions.

4.4. Subjects

The same four subjects were employed in all conditions of both experiments. Two were Columbia undergraduates who had served as subjects in prior experiments; although they were familiar with the general procedures, they were naive about the purposes of the present experiments. The other two were the two authors who had served as subjects in a number of related experiments. (See Li and Matin (1996a) for some control procedures).

5. Results

5.1. Pitched-from-vertical and oblique 2-line combinations of parallel or equal-and-opposite orientations

The results for two subsets of the 2-line stimuli from each of the two experiments will be described before considering the results of each of the two experiments in full. This will permit a clearer and simpler development leading from our previous experiments with parallel lines. From Experiment 1 the subset consists of the seven parallel, pitched-from-vertical pairs of stimuli (Fig. 2(a)) and the seven pairs of stimuli for which the two members of a pair had pitches of equal magnitude but opposite orientation (Fig. 2(c)). From Experiment 2 the subset consists of the seven pairs of parallel stimuli (same projected orientation as equal-and-opposite, pitched-from-vertical pairs in Experiment 1 (Fig. 2(d)) and the seven pairs of mirror symmetrical stimuli (same projected orientations as parallel, pitched-from-vertical pairs in Experiment 1 (Fig. 2(b)).

5.1.1. Pitched-from-vertical 2-line combinations

Fig. 3(a) displays the VPELs averaged across the four subjects for the seven 2-line combinations for which the two pitched-from-vertical lines were parallel (unfilled squares). Along with these results are displayed average VPELs for the same four subjects from the earlier experiment in which they viewed only one of the two lines at a time (Li and Matin, 1996a). The small increase of the slope of the average VPEL-versus-pitch function from 0.36 for each of the two 1-line conditions to 0.44 for the parallel 2-line combination is typical for long lines and fits near the asymptote of a negatively accelerated exponential growth function of total line length (Matin and Li, 1994b). The results with the 2-line stimulus in Fig. 4(a) are very similar to those reported in the earlier article where, with the same apparatus, the average slope for the same four subjects was 0.40. As reported previously (Matin and Fox, 1989; Matin and Li, 1992a, 1995b), the VPEL measured in darkness (filled circle at abscissa zero) falls a few de-

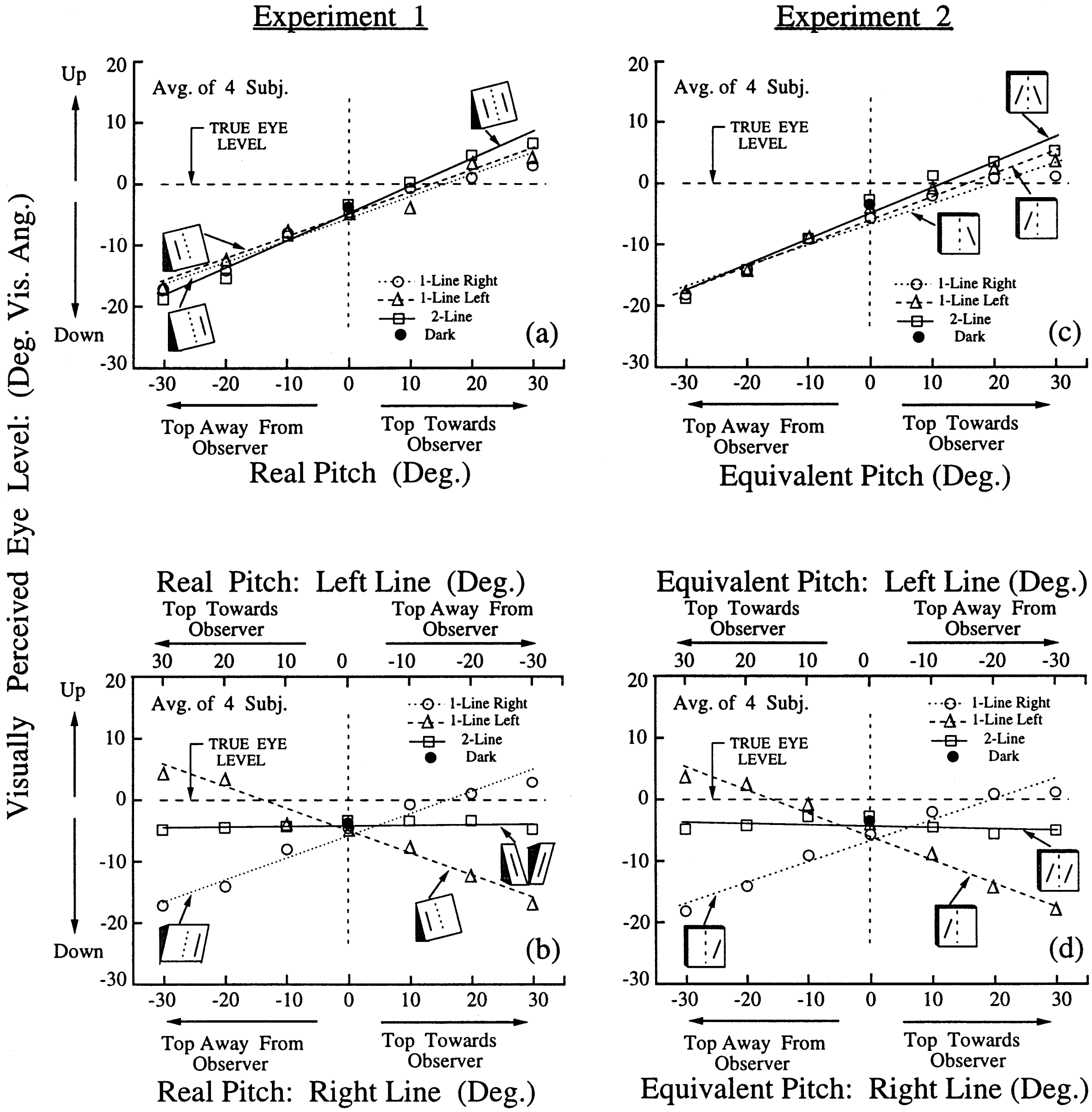

Fig. 3. Visually perceived eye level (VPEL) from Experiment 1 for the parallel pitched-from-vertical 2-line visual field (a), and for the visual fields consisting of equal-and-opposite pitched-from-vertical 2-line pairs (b). VPELs from Experiment 2 for the oblique 2-line equivalent-pitch counterparts of (a) and (b) are displayed in (c) and (d), respectively. Since the 2-line data in (a) and in (b) were obtained in the same sessions the same dark value is shown in both panels; similarly for the dark values shown in (c) and (d). The 1-line data shown in each of the panels is from a previously-reported experiment carried out under identical conditions on the same subjects (Li and Matin, 1996a). All VPEL values are average values for the same four subjects. The solid straight line in each panel is the line of best fit to the 2-line results; the dashed and dotted lines are the lines of best fit to the VPEL values for the 1-line left and 1-line right line conditions from the previously-reported experiment.

grees below true eye level; the VPEL shown is the average across the seven sessions of Experiment 1 for all four subjects.

The results are quite different when the two simultaneously-presented lines arise from planes whose pitches possess equal magnitude but opposite orientation as shown by the unfilled squares in Fig. 3(b). The average results for each of the 1-line conditions shown in Fig. 3(a) are plotted again in Fig. 3(b), this time with the horizontal axis for the left pitched-from-vertical line reversed so that the results for both of the 1-line stimuli that were combined in a given 2-line equal-and-opposite-pitch view are plotted at the same abscissa location as the results for the corresponding 2-line condition. In this case the simultaneous viewing of two lines of equal and opposite pitch results in nulling of the influence of one line by that of the other so that the net influence from the different 2-line combinations in Fig. 3(b) do not differ from each other (slope = 0.01), and the average VPEL values obtained hardly differ at all from the

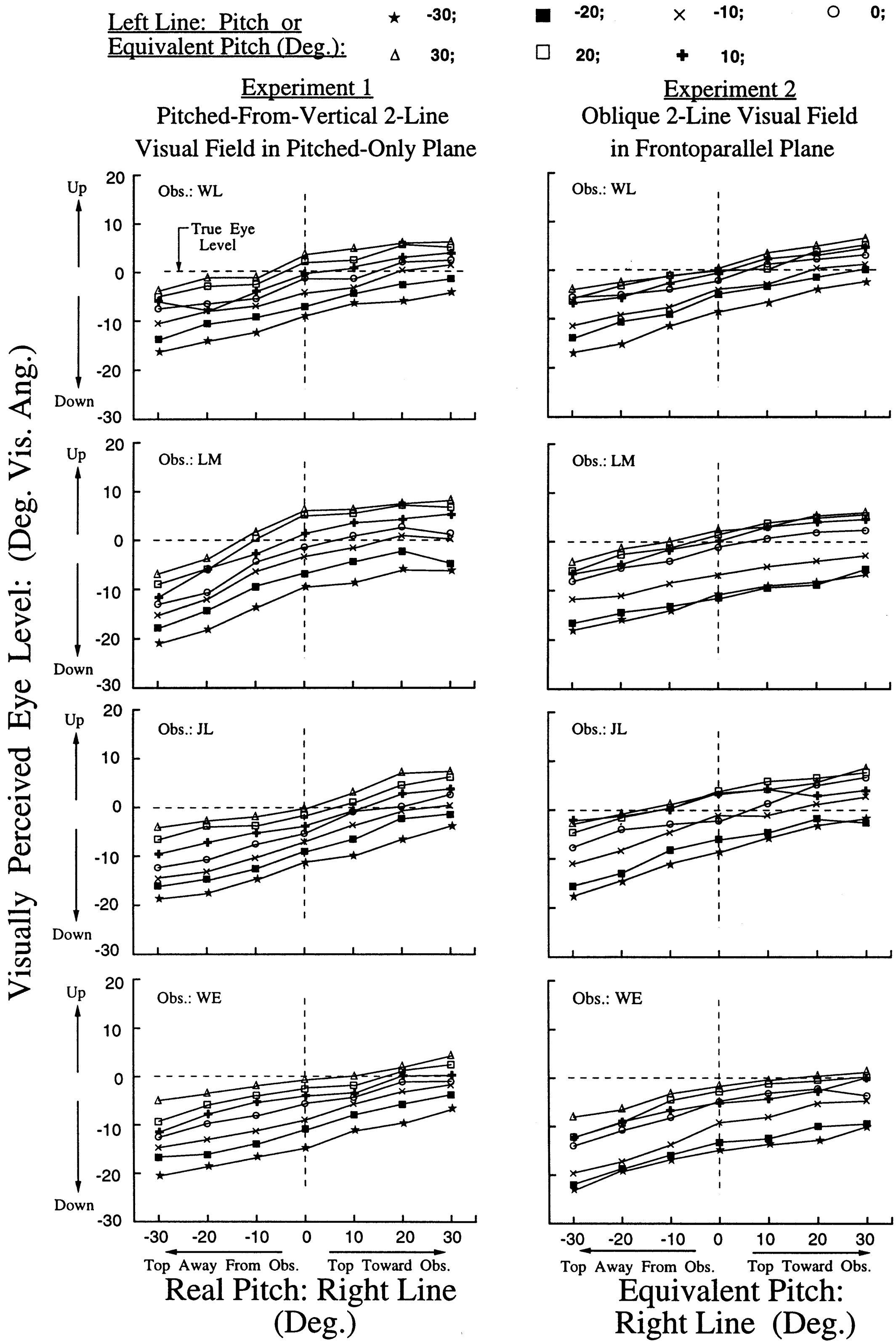

Fig. 4. The panels in the lefthand column display the complete results for the 49 conditions of Experiment 1 for each subject separately, those in the righthand column for those of Experiment 2. Each value of visually perceived eye level (VPEL) is plotted with the pitch of the right line on the abscissa and the pitch of the left line as the parameter whose value is indicated by the symbol in the legend at the top of the figure.

average VPEL measured in the dark across the seven sessions.

5.1.2. Oblique 2-line combinations

Fig. 3(c) displays the VPELs in Experiment 2 averaged across the four subjects for the seven orientations in which the 2-line stimuli originated from the erect plane at orientations that were projected to the identical loci (lines of equivalent pitch) that were struck by the parallel, 2-line, pitched-from-vertical stimuli in Fig. 3(a). Along with these results are displayed average VPELs for the same four subjects from the earlier article in which they viewed only one of the two oblique lines at a time (Li and Matin, 1996a). The small increase of the slope of the average VPEL-versus-equivalent-pitch function from 0.38 and 0.34 for the left and right 1-line conditions, respectively, to 0.42 for the 2-line condition is very similar to that reported in the earlier article for these four subjects where the 2-line result was 0.40. Thus the influences on VPEL of stimuli originating from an erect plane do not differ from the influences originating from pitched planes providing that the line stimuli from the erect and pitched planes stimulate the same projected orientation. Again, as in Experiment 1, the VPEL measured in darkness falls slightly below true eye level; the dark VPEL is the average across the seven sessions of Experiment 2 for all four subjects.

Fig. 3(d) displays the results with the parallel 2-line stimuli of equivalent pitch to the real pitch orientations in Fig. 3(b). Their relation to the two 1-line stimuli from the erect plane (reproduced in Fig. 3(d) with reversed relation between left-line and right-line axes from Fig. 3(c)) is very similar to that of the VPEL-versus-pitch function with equal-and-opposite real pitch in Fig. 3(b). Here the slope is equal to -0.02. Thus, an identity of behavior of lines from different planes holds true for the 2-line equal-and-opposite case (Fig. 3(b, d)) as it does for the individual line and the 2-line parallel pitched-from-vertical case (Fig. 3(a, c)).

5.1.3. Summary

In addition to reporting that the slope of the VPEL-versus-pitch function for the parallel, pitched-from-vertical 2-line stimulus is slightly greater than the slope for the 1-line stimulus (Fig. 3(a)) and is indistinguishable from the slope for the mirror symmetric oblique lines of equivalent pitch in the frontoparallel plane (Fig. 3(c)) as previously described (Li and Matin, 1996a), there are two main pieces of news in Fig. 3: (a) bilaterally symmetric combinations of two pitched-from-vertical lines of equal-and-opposite orientation null each other's individual effects on VPEL (Fig. 3(b)) and result in no net influence. (b) The equivalence relation between pitched-from-vertical lines and oblique lines is extended further and shown to hold between the equal-and-opposite 2-line pitched-from-vertical stimulus and the parallel oblique stimulus in an erect plane (Fig. 3(b, d)).

The results for equal-and-opposite pitches (Fig. 3(b)) suggests the operation of a rule of algebraic averaging between the separate influences from the two lines so that, for example, whereas a single line on the right side of the median plane pitched topforward by 30° might produce an elevation in VPEL of 12° and a line on the left side pitched topbackward might produce a declination of 12° relative to the dark VPEL, together they produce no net effect. This points to the operation of an opponent mechanism. However, the nulling could be accounted for either by a mechanism employing algebraic addition or by a mechanism that generates an average of its inputs, and, the results in Fig. 3(b, d) do not provide a basis for distinguishing between them; either would do. Although the closeness of the 1-line and 2-line results in Fig. 3(a, c) are close to expectations for an averaging mechanism, the departure indicates a small influence of algebraic addition ('summation'). The full results from Experiments. 1 and 2 provide a clearer basis for an interpretation that involves both summation and averaging as limiting processes; these are noted below.

5.2. The complete experiments: 49 2-line combinations/experiment

The results for each of the individual subjects in all 49 2-line conditions of Experiments 1 and 2 are shown in the left and right columns of Fig. 4, respectively. Average values across the four subjects for each experiment are displayed in Fig. 5. In these figures the pitch of the plane containing the right line is displayed on the abscissa with the pitch of the plane containing the left line as the parameter of the set of functions. Each straight line through the data in Fig. 5 is the least squares best-fit to the VPEL-versus-right-line-pitch data with one left-line pitch (equivalent pitch); the fit was carried out independently of the fits with the other left-line pitches (equivalent pitches) as parameter. The slope and y-intercepts of the best fits to the average values are plotted in Fig. 6(a, b), respectively, and listed in Table 1 along with values from fits in which the roles of left and right lines are reversed (i.e. each slope and y-intercept were calculated from a best fit to the same data in which the pitch (equivalent pitch) of the right line (the parameter) was fixed and the pitch (equivalent pitch) of the left line varied). Best-fitting slopes and y-intercepts for the individual subjects are also listed in Tables 1 and 2.

The most prominent aspect of the results in Figs. 4 and 5 is the monotonic increase in the level of each nearlinear data set with increased topforwardness (or equivalent topforwardness) of the pitch of the lefthand line. This increase is most simply characterized by the

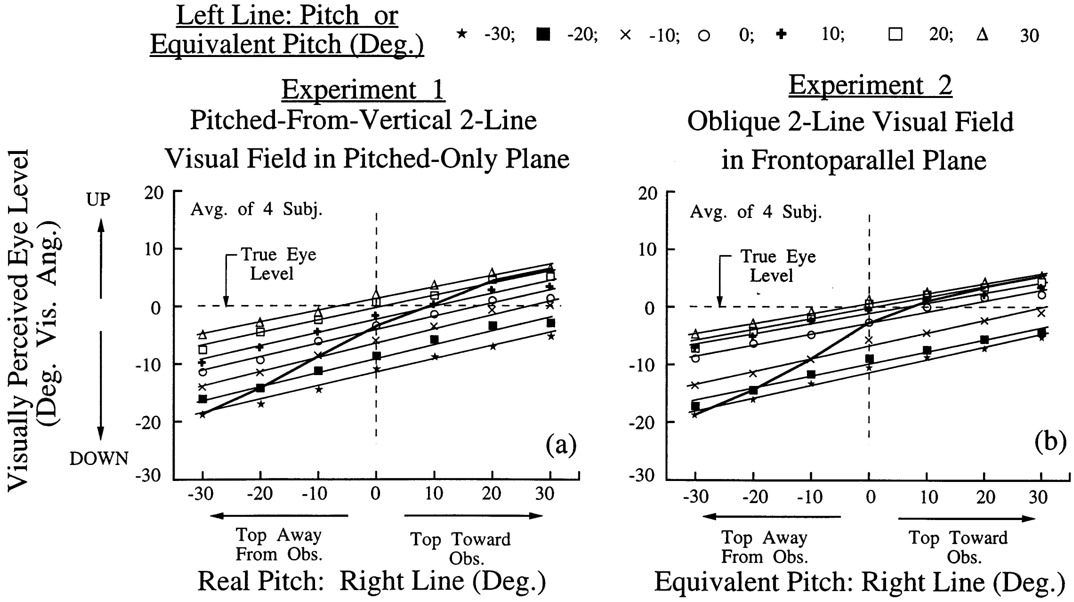

Fig. 5. The average values of visually perceived eye level (VPEL) across the four subjects for all of the 49 conditions in Experiments 1 and 2 are displayed in panels (a) and (b), respectively. Each VPEL is plotted with the pitch of the right line on the abscissa and the pitch of the left line as the parameter whose value is indicated by the symbol in the legend at the top of the figure. Each straight line is a line of best-fit to the seven points with the same left-line pitch under variation of the pitch of the right line (least squares criterion). The dark solid line in each panel connecting adjacent points with different left line pitches runs through the set of seven points for the parallel pairs in (a) and the seven oblique pairs of equivalent pitch in (b).

increase in the value of the y-intercept with increased topforwardness of the pitch of the left line. The y-intercept values from the best fits to the average data are plotted in Fig. 6(b) as the open squares (Experiment 1) and open circles (Experiment 2), with no significant differences in the values between the two experiments (Tables 1 and 2), and with generally small differences when the roles of the left and right lines are interchanged as parameter and variable; the essential identity with and without the interchange indicates that there are at most minor departures from bilateral symmetry in the processing of the two lines in each experiment.

In addition to the near-linearity of the functions and the monotonicity of the series of functions in Figs. 4 and 5 two features of the results in those figures and one additional feature present in Tables 1 and 2 stand out:

(1) In Figs. 4 and 5 the vertical separations between the VPEL-versus-pitch functions decrease with increasing topforwardness of the pitch of the parameterized line. For example, in Experiment 1 the 1.6° difference between the best-fitting y-intercepts in Fig. 5 for the + 20 and + 30° pitches of the left line is equal to 59% of the vertical separation of 2.7° between the left line pitches of − 30 and − 20°; the corresponding value for Experiment 2 is 57% where the + 20 to + 30° and − 30 to. − 20° differences are 0.8 and 1.4° respectively (see Tables 1 and 2 and Fig. 6(b)).

(2) Although the functions in Figs. 4 and 5 are fairly linear the average best-fitting slopes and those of three of the four individual subjects diminish regularly with increasing pitch of the left line, resulting in a small convergence of the set of functions toward the right in the figures; for the averages in Experiment 1 the slopes in Fig. 5 decrease from a high of 0.24 for the lowest data set to a low of 0.20 for the uppermost data set (Fig. 6(a)); in Experiment 2 the slope decreases from a high of 0.23 to a low of 0.17.

(3) As noted above, reversal of the roles of the left and right lines as parameter and variable of the fittings results in closely similar behavior of the y-intercepts and slopes to those without reversal (the similarity is most obvious in Fig. 6). As for the results in Tables 1 and 2, with increased topforwardness of the pitch of the right line the reversed plots (not graphed) also show a monotonic increase in the level of the VPEL-versus-pitch function, closer spacing between the data sets, and a decrease in the slope of the function; for the reversed real pitch case the vertical separation between the two most topforward right-line average functions is 33% of the vertical separation between the two most topbackward conditions and the slope decreases from a high of 0.22 to a low of 0.19; for the reversed equivalent pitch results the corresponding value is 46% and the slope decreases from a high of 0.25 to a low of 0.19.

The results with equivalent pitch match those with real pitch fairly closely. Fig. 7 adds to this aspect of the picture. In Fig. 7(a) the 196 individual VPELs from each of the two experiments are plotted against each other: each point in Fig. 7(a) plots the VPEL for a given pitch versus the VPEL for the equivalent pitch for one subject. Fig. 7(b) plots the same pairing for the average VPELs across subjects for each of the 49 matched conditions. The best fitting slope is less than 1 in each case (0.93 and 0.94) indicating a slightly less rapid growth of VPEL with change in orientation for the oblique lines than for the pitched-from-vertical lines. Since the roles of the left and right line were interchanged in the experimental design of the two experiments (parameter and variable within a session were reversed in Experiment 2 from the order in Experiment 1; see Method Section), the similarity of slopes and of y-intercepts in the two experiments (Fig. 7) indicates a high degree of insensitivity to the role reversal and further indicates the bilateral symmetry.

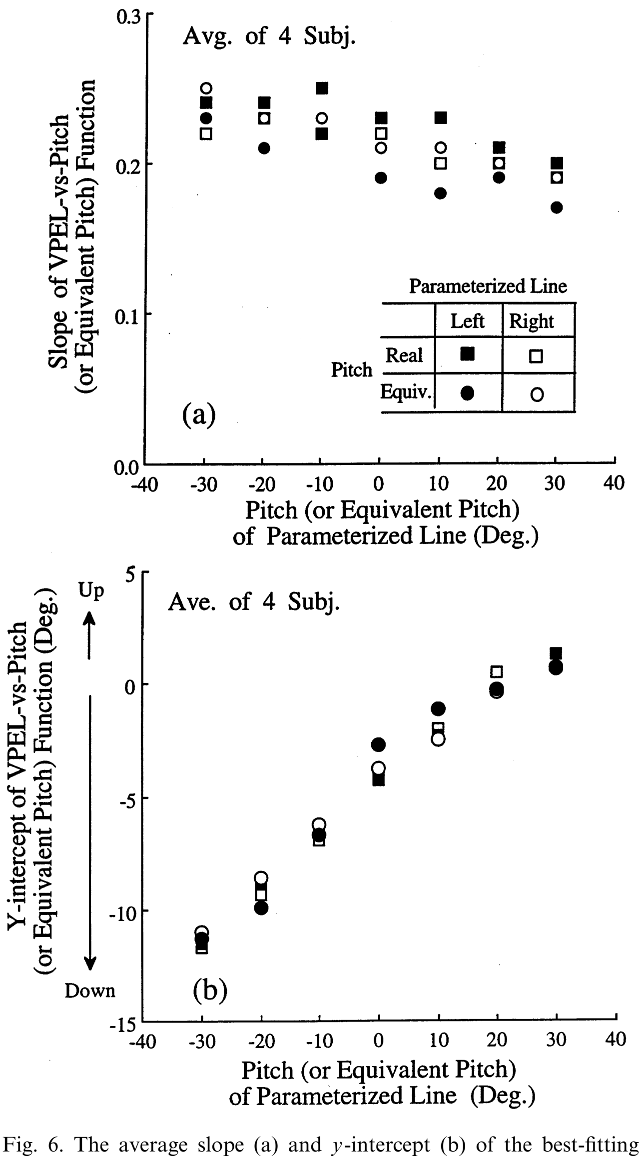

Fig. 6. The average slope (a) and y-intercept (b) of the best-fitting VPEL-versus-pitch (Experiment 1) or VPEL-versus-equivalent-pitch straight line function (Experiment 2) is displayed on the ordinate with the pitch (or equivalent pitch) of the parameterized line on the abscissa; the other (nonparameterized) line is the variable of the function. The values displayed with left line parameterized are those displayed in Fig. 5.

This similarity of the y-intercepts as well as the slopes with and without reversal of the roles of the left and right lines (Table 1; Fig. 6) is closely related to a significant result of the two experiments that has not yet been noted: The slopes of the VPEL-versus-pitch functions in Experiment 1 for the functions with the pitch of one line fixed and the second line variable (49 conditions in Fig. 5(a)) are very close to 1/2 the values of the slopes for the parallel, pitched-from-vertical 2-line condition ('same-pitch condition') that were separated out in Fig. 3(a) (Fig. 8(a)); the ratio is also 1/2 in Experiment 2 for the analogous equivalent pitch functions. The average of the slopes across all four subjects and seven functions for each subject in Experiment 1 is + 0.22, the average for the parallel condition is + 0.44; in Experiment 2 the average slope across all four subjects and seven functions for each subject is 0.20; the average for the same equivalent-pitch condition is 0.42. The heavy solid lines in Fig. 5(a, b) connect the subset of the average results that constitutes the same-pitch condition displayed in Fig. 3 above. Fig. 8(a) shows that, although there is some variation of the slopes among the individual subjects, this 2:1 ratio holds for each subject in each experiment; the y-intercepts, however, do not differ significantly (Fig. 8(b)).

5.3. Reliability and consistency of an individual subject's VPEL settings

The standard deviations (SDs) of the four VPEL settings across all two-line conditions and all subjects averaged 0.61° and 0.56° in Experiments 1 and 2, respectively, and 0.97° and 1.07° in darkness. These values are very close to those previously reported where SDs in the presence of pitched-from-vertical line stimuli averaged 0.7° and in darkness averaged 0.99° (Matin and Li, 1994a).

The slopes for a given individual in the two experiments are generally close (Tables 1 and 2) compared to the range of average slopes among subjects; a similar result holds for the two average y-intercepts (Tables 1 and 2). The differences between the values for a given subject between the two experiments are small and appear to be random.

A closer look at the consistency of an individual subject is afforded by Fig. 7(a). The marked correlation of VPELs across the two experiments— + 0.91—is, of course, in part a consequence of the third variable, pitch/equivalent pitch. However, the average correlation between the VPELs in the two experiments for a given one of the 49 combinations of pitch/equivalent pitch (essentially a partial correlation) is itself substan-

Table 1
Experiment 1: VPEL values and best fitting parameters for pitched-from-vertical 2-line stimulus in pitched-only plane

Subject	Pitch angle of left line (Deg)		Pitch angle of right line (Deg)							Slope	y-intercept
			Topbackward			Erect	Topforward				
			30	20	10	0	10	20	30		
JL	Topbackward	30	18.2D	17.2D	14.4D	11.0D	9.6D	6.3D	3.4D	0.25	11.4D
	↑	20	16.1D	14.6D	12.6D	9.0D	6.6D	2.4D	1.4D	0.27	8.9D
		10	14.6D	13.1D	10.3D	7.1D	3.6D	0.7D	0.5U	0.28	7.0D
	Erect	0	12.3D	10.6D	7.4D	5.3D	0.9D	0.2U	2.6U	0.26	4.8D
		10	9.3D	7.4D	5.7D	3.6D	0.5D	3.1U	4.1U	0.24	2.8D
	↓	20	6.4D	3.8D	3.7D	1.6D	1.1U	4.6U	6.2U	0.21	0.5D
	Topforward	30	4.0D	2.9D	2.0D	0.3D	3.2U	7.2U	7.4U	0.21	1.2U
		Slope	0.24	0.25	0.21	0.18	0.20	0.21	0.18		
		y-intercept	11.6D	9.9D	8.0D	5.4D	2.4D	0.8U	2.3U.		
LM	Topbackward	30	20.5D	17.6D	13.4D	9.0D	8.6D	5.6D	5.9D	0.26	11.5D
	↑	20	17.7D	14.3D	9.6D	6.7D	4.4D	2.3D	4.7D	0.24	8.5D
		10	15.2D	12.0D	6.3D	3.3D	1.5D	0.9U	0.3U	0.28	5.3D
	Erect	0	13.1D	10.6D	4.2D	1.3D	0.9U	2.9U	1.6U	0.27	3.4D
		10	11.7D	5.7D	2.4D	1.7U	3.9U	4.4U	5.6U	0.28	0.6D
	↓	20	8.9D	5.8D	0.5U	4.8U	5.7U	7.3U	6.9U	0.28	1.5U
	Topforward	30	6.8D	3.7D	1.7U	5.7U	6.5U	7.8U	8.4U	0.26	2.8U
		Slope	0.22	0.23	0.25	0.26	0.25	0.22	0.25		
		y-intercept	13.4D	9.9D	4.8D	1.2D	0.3U	2.2U	1.7U		
WE	Topbackward	30	20.3D	18.4D	16.4D	14.7D	10.8D	9.3D	6.3D	0.24	13.7D
	↑	20	16.8D	16.4D	14.2D	11.1D	8.0D	6.1D	3.9D	0.23	10.9D
		10	14.8D	13.1D	11.3D	9.2D	5.7D	3.2D	1.9D	0.23	8.4D
	Erect	0	12.7D	9.8D	8.1D	5.7D	4.4D	1.2D	1.1D	0.20	6.2D
		10	11.4D	7.7D	5.2D	4.0D	3.4D	0.2U	0.4U	0.19	4.4D
	↓	20	9.5D	5.9D	4.0D	2.7D	1.9D	1.2U	2.5U	0.19	2.9D
	Topforward	30	5.1D	3.6D	2.9D	0.7D	0.0	2.0U	4.3U	0.15	0.9D
		Slope	0.23	0.25	0.24	0.23	0.17	0.18	0.17		
		y-intercept	12.9D	10.7D	8.9D	6.8D	4.9D	2.2D	0.9D		
WL	Topbackward	30	16.0D	13.9D	12.3D	8.7D	6.1D	6.1D	3.9D	0.21	9.6D
	↑	20	13.8D	10.7D	9.2D	7.2D	4.4D	2.8D	1.4D	0.21	7.1D
		10	10.6D	7.7D	6.3D	4.3D	3.2D	0.3U	1.5U	0.20	4.3D
	Erect	0	7.8D	6.7D	4.9D	1.4D	1.4D	2.1U	2.8U	0.19	2.5D
		10	6.1D	7.8D	3.9D	0.2D	1.0U	3.4U	3.8U	0.20	1.4D
	↓	20	5.0D	2.4D	2.6D	2.0U	2.6U	5.6U	5.0U	0.18	0.8U
	Topforward	30	3.9D	1.2D	1.4D	3.6U	4.9U	6.1U	6.2U	0.18	2.0U
		Slope	0.21	0.21	0.17	0.21	0.18	0.20	0.16		
		y-intercept	9.0D	6.8D	5.8D	2.3D	1.0D	1.2U	2.0U		
Average of four subjects	Topbackward	30	18.8D	16.8D	14.1D	10.9D	8.8D	6.8D	4.9D	0.24	11.6D
	↑	20	16.1D	14.0D	11.4D	8.5D	5.9D	3.4D	2.8D	0.24	8.9D
		10	13.8D	11.5D	8.6D	5.9D	3.5D	0.6D	0.1U	0.25	6.3D
	Erect	0	11.5D	9.4D	6.2D	3.4D	1.4D	1.0U	1.4U	0.23	4.2D
		10	9.6D	7.2D	4.3D	1.5D	0.3U	2.8U	3.5U	0.23	2.3D
	↓	20	7.5D	4.5D	2.5D	0.6U	1.9U	4.7U	5.1U	0.21	0.3D
	Topforward	30	5.0D	2.8D	1.1D	2.1U	3.6U	5.8U	6.6U	0.20	1.3U
		Slope	0.22	0.23	0.22	0.22	0.20	0.20	0.19		
		y-intercept	11.7D	9.3D	6.9D	3.9D	2.0D	0.5U	1.3U		

U and D refer to settings above and below true eye level, respectively, VPEL denotes visually perceived eye level.

tial — + 0.55—and is completely free of any influence of the pitch/equivalent pitch variable. That indicates a great deal of consistency in the VPEL settings of a given subject across the pitched and roll-tilted conditions.

5.4. Dark VPELs

The dark VPELs generally fell below true eye level, with averages across the seven sessions in Experiments 1 and 2 equal to − 3.75 and − 3.37, respectively. The average dark VPEL across subjects in each of the 14 sessions fell below true eye level. The values fell below true eye level in all 28 individual sessions in Experiment 1 and in 23 of the 28 individual sessions in Experiment 2. The average dark VPEL fell slightly below the average VPEL measured against the erect 2-line stimulus (0.32 and 0.76° in Experiments 1 and 2, respectively), well within a range that might be

Table 2
Experiment 2: VPEL values and best fitting parameters for oblique 2-line stimulus in frontoparallel plane

Subject	Equivalent pitch angle of left line (Deg)		Equivalent pitch angle of right line (Deg)							Slope	y-intercept
			Topbackward			Erect	Topforward				
			30	20	10	0	10	20	30		
JL	Topbackward	30	17.4D	14.4D	11.9D	8.4D	5.4D	3.0D	1.6D	0.27	8.9D
	↑	20	15.6D	13.0D	8.1D	6.1D	4.5D	1.8D	2.6D	0.23	7.4D
		10	10.9D	8.4D	4.6D	1.2D	1.0D	1.3U	2.9U	0.23	3.1D
	Erect	0	7.7D	4.0D	3.0D	2.1D	1.3U	5.2U	6.6U	0.23	0.5D
		10	2.3D	0.9D	0.4U	3.5U	4.2U	3.0U	4.3U	0.11	1.7U
	↓	20	4.5D	1.5D	0.6U	4.0U	6.0U	6.7U	7.7U	0.21	2.7U
	Topforward	30	2.5D	0.8D	1.3U	3.3U	4.1U	5.9U	8.5U	0.18	2.8U
		Slope	0.27	0.25	0.22	0.21	0.20	0.16	0.19		
		y-intercept	8.7D	6.1D	3.6D	1.0D	0.7D	2.5U	3.7U		
LM	Topbackward	30	17.8D	15.3D	13.5D	10.5D	9.2D	8.3D	6.3D	0.19	11.6D
	↑	20	16.7D	14.4D	13.1D	11.5D	9.4D	8.8D	5.8D	0.17	11.4D
		10	11.8D	10.9D	8.7D	6.8D	5.2D	3.9D	2.8D	0.16	7.2D
	Erect	0	8.1D	5.4D	4.0D	1.1D	1.0U	1.9U	2.3U	0.18	1.9D
		10	6.4D	4.5D	1.5D	0.4U	3.1U	4.3U	4.7U	0.20	0.0
	↓	20	6.0D	2.3D	1.3D	1.6U	3.8U	5.1U	5.4U	0.19	0.9U
	Topforward	30	4.3D	1.4D	0.0	2.5U	3.1U	5.2U	5.7U	0.17	1.6U
		Slope	0.24	0.26	0.25	0.26	0.26	0.27	0.24		
		y-intercept	10.1D	7.7D	6.0D	3.6D	1.8D	0.6D	0.5U		
WE	Topbackward	30	22.6D	19.2D	16.7D	14.7D	13.3D	12.5D	9.9D	0.20	15.6D
	↑	20	22.2D	18.7D	16.2D	13.4D	12.6D	10.0D	9.8D	0.21	14.7D
		10	19.9D	17.3D	13.7D	9.3D	8.1D	5.5D	4.8D	0.27	11.2D
	Erect	0	14.1D	10.7D	8.1D	4.9D	3.3D	2.3D	3.8D	0.19	6.8D
		10	12.1D	8.8D	6.7D	5.0D	4.2D	2.4D	0.1U	0.19	5.6D
	↓	20	12.1D	9.1D	4.6D	3.0D	1.3D	0.6D	0.1U	0.20	4.4D
	Topforward	30	8.1D	6.5D	3.5D	1.7D	0.8D	0.3U	1.3U	0.16	2.7D
		Slope	0.25	0.23	0.25	0.23	0.23	0.22	0.21		
		y-intercept	15.9D	12.9D	9.9D	7.4D	6.2D	4.7D	3.8D		
WL	Topbackward	30	17.0D	15.2D	11.5D	8.4D	6.5D	3.5D	2.3D	0.25	9.2D
	↑	20	14.1D	10.8D	9.0D	5.1D	3.2D	1.7D	0.2U	0.24	6.3D
		10	11.5D	9.5D	8.4D	4.3D	3.1D	0.0	1.1U	0.22	5.1D
	Erect	0	5.4D	4.9D	4.0D	2.3D	1.0U	2.4U	3.1U	0.16	1.4D
		10	6.8D	5.6D	2.7D	0.8D	2.1U	3.5U	4.9U	0.21	0.8D
	↓	20	6.2D	3.3D	1.0D	0.1D	0.2U	3.6U	5.0U	0.17	0.2D
	Topforward	30	3.9D	2.6D	1.0D	0.1U	2.7U	4.8U	6.4U	0.18	0.9U
		Slope	0.22	0.20	0.19	0.14	0.14	0.14	0.14		
		y-intercept	9.3D	7.4D	5.4D	3.0D	1.0D	1.3U	2.6U		
Average of four subjects	Topbackward	30	18.7D	16.0D	13.4D	10.5D	8.6D	6.8D	5.1D	0.23	11.3D
	↑	20	17.2D	14.2D	11.6D	9.0D	7.4D	5.6D	4.5D	0.21	9.9D
		10	13.5D	11.5D	8.8D	5.4D	4.4D	2.0D	0.9D	0.22	6.6D
	Erect	0	8.8D	6.3D	4.8D	2.6D	0.0	1.8U	2.1U	0.19	2.7D
		10	6.9D	5.0D	2.6D	0.5D	1.3U	2.1U	3.5U	0.18	1.2D
	↓	20	7.2D	4.1D	1.6D	0.6U	2.2U	3.7U	4.6U	0.19	0.2D
	Topforward	30	4.7D	2.8D	0.8D	1.1U	2.3U	4.0U	5.5U	0.17	0.6U
		Slope	0.25	0.23	0.23	0.21	0.21	0.20	0.19		
		y-intercept	11.0D	8.6D	6.2D	3.8D	2.4D	0.4D	0.7U		

U and D refer to settings above and below true eye level, respectively, VPEL denotes visually perceived eye level.

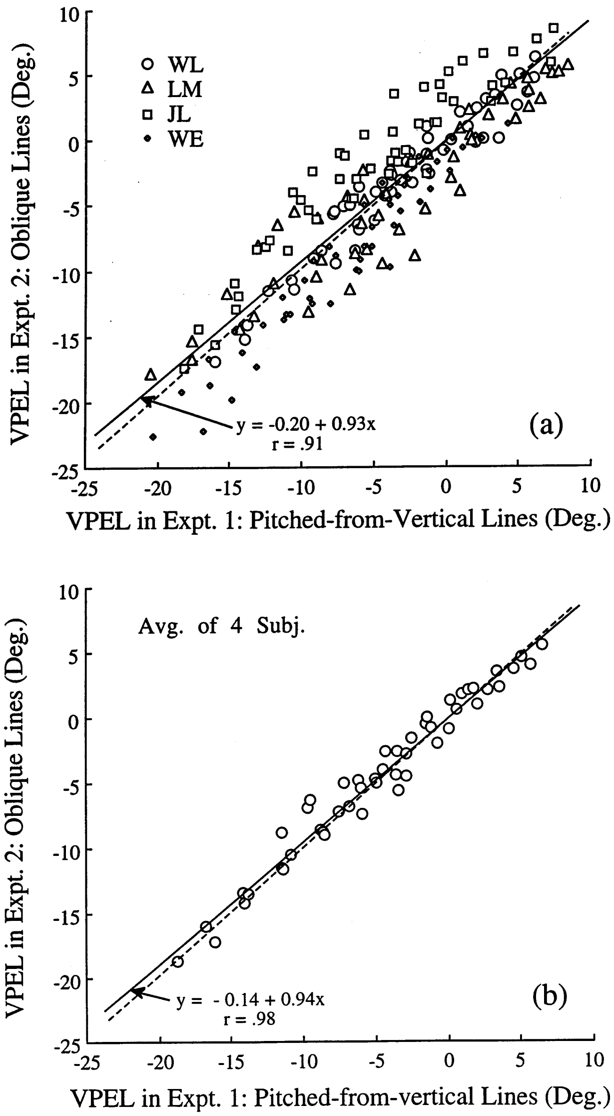

Fig. 7. (a) Each of the VPELs in Experiment 1 with the 2-line pitched-from-vertical visual field (196 VPELs = 49 conditions × four subjects) is plotted on the abscissa against the VPEL from the condition with equivalent pitch for the same subject in Experiment 2 on the ordinate. (b) Each of the 49 VPELs averaged across the four subjects in Experiment 1 is plotted against the average VPEL in the equivalent pitch condition of Experiment 2. The equation displayed in each panel is the best-fitting straight line. The best fits are shown as the solid lines; the dashed diagonal line is the slope-of-1.00 line.

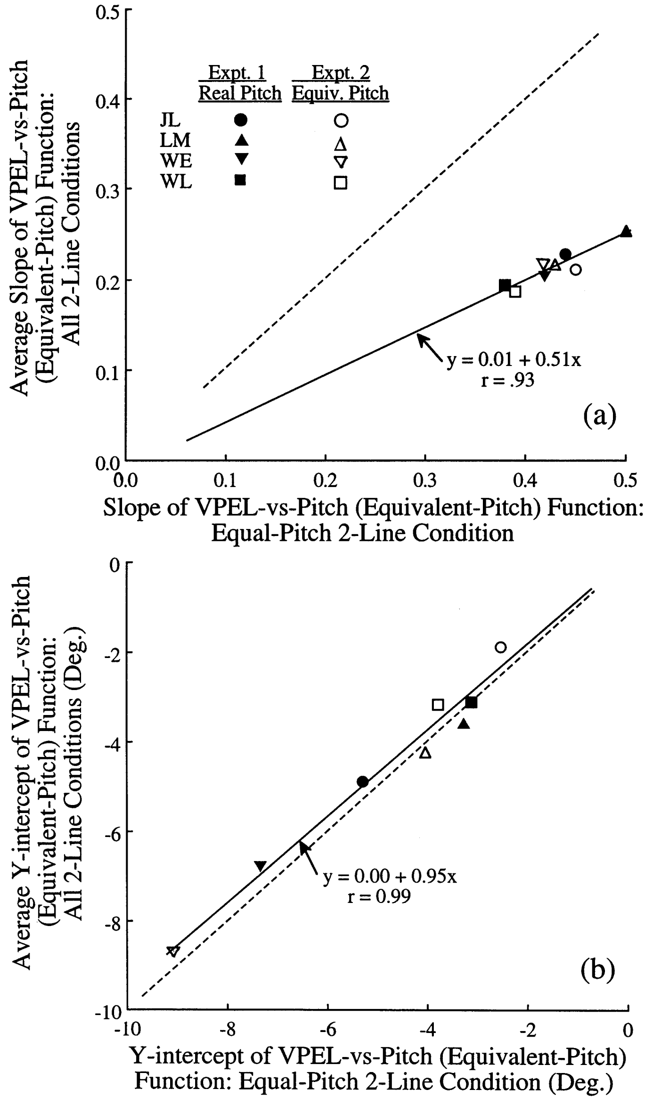

Fig. 8. (a) The average slope of the seven best-fitting straight lines to the VPEL-versus-pitch functions in Fig. 4(a) for each subject in Experiment 1 is plotted against the slope of the VPEL-versus-pitch function for the parallel 2-line pitched-from-vertical results only; the average slope of the seven best-fitting straight lines to the VPEL-versus-equivalent pitch functions in Fig. 4(b) for each subject in Experiment 2 is plotted against the slope of the VPEL-versus-equivalent pitch function for the 2-line bilaterally symmetric oblique results only. The solid line through the data is the best-fitting straight line to the eight points. (b) The averages of the y-intercepts of the best-fitting straight lines noted in (a) are plotted against each other. The diagonal line in each panel is the slope-of-1.00 line.

expected from previous work. It is of some interest to note that the intersection points of both the 1-line and 2-line best-fitting VPEL-versus-pitch functions at the zero abscissa fell very close to the dark VPELs (Fig. 3). Although it will not be further dealt with in this article we note that this is in agreement with the view (Matin and Fox, 1989; Matin and Li, 1992a, 1995b) that the visual influence arises from a separate source than the one generating the dark value.

6. Discussion

6.1. Main characteristics of the results

The near identity of the results for the 49 pitched-from-vertical 2-line conditions in Experiment 1 and the 49 equivalent pitch conditions in Experiment 2 extends the earlier results with 1-line and parallel 2-line stimuli that had led to the conclusion that the significant aspects of the visual stimulus determining the influence on VPEL are the orientation and eccentricity of the image of the line on the projection sphere centered at the nodal point of the eye (Matin and Li, 1992a, 1994a,b,c; Li and Matin, 1996a). The correspondence in the present results holds between 2-line combinations of pitched-from-vertical lines in pitched-only planes at all orientations and their oblique equivalent-pitch counterparts from the erect plane. Throughout the discussion, then, we will assume that the important aspect of a line's orientation for VPEL is defined by its nodal plane (Fig. 1). However, although the results of our previous experiments with parallel lines only demonstrated significant summation between simultaneously-presented members of a parallel line pair, as we will discuss further below, the results of the present experiments with line pairs for which the two lines in a pair are set at different orientations demonstrate both summation and averaging as key aspects for both parallel and nonparallel lines, with averaging by far the more prominent aspect.

Seven aspects of the results will play key roles in the subsequent discussion: (a) the nearlinearity of the VPEL-versus-pitch functions for both the 1-line and 2-line stimuli (Figs. 3–5), (b) the roughly parallel character of the VPEL-versus-pitch functions for the 2-line stimuli with one of the lines as variable and the other as parameter (Figs. 4 and 5), (c) the slightly smaller slopes for the 1-line functions as compared to the functions for two simultaneously-presented parallel lines– –an indication of summation (Fig. 3), (d) the reduced deviation of the elevation of VPEL from the dark value produced by one line when a second line is added that is pitched at a smaller angle than the first line; (e) when the second simultaneously-presented line is pitched at a larger angle in the direction opposite the first line the VPEL deviation reverses from the direction produced by the first line alone (Fig. 3(b, d), 4, 5), (f) the strong indications of averaging of the influences from different orientations (Fig. 3(b, d), 4, 5), (g) although nearly parallel, the VPEL-versus-pitch functions with one of the lines as variable and the other as parameter manifests convergence to the right on the graphs, and the functions become more closely spaced as the parameter's pitch becomes more topforward (Figs. 4 and 5).

Some of the above properties are indicated as 'near'– –thus: 'nearparallel', 'nearlinear', 'near-equally-spaced', 'nearaveraging'. The deviations that require us to include 'near' in each of their decriptions are too clear and consistent to be overlooked or passed off as the product of experimental variability. They play an important role in guiding us to our theoretical treatment of the mechanism controlling the production of VPEL. Some aspects of a model of the visual influence on VPEL that is centered on the present results will be described below; the detailed development will be presented in a subsequent article (in preparation) in the context of additional experiments with pairs and trios of short nonparallel lines (in preparation).

6.2. Extraction of three significant features from the results

The discussion below will be developed in three phases: (1) In Section 6.2.1 we focus on the fact that the influence on the elevation of VPEL by any 2-line combination is, to a first approximation, equal to the algebraic average of the independent influences of the two lines. (2) In Section 6.2.2 we describe the presence of summation between the influences of individual lines, are able to conclude that it operates among nonparallel lines as well as parallel lines, and juxtapose it with the presence of averaging. (3) In Section 6.2.3 we delineate the features in the present results that indicate opponency in the mechanism mediating the visual influence on VPEL.

6.2.1. Averaging

Fig. 9(a, b) replot the data points displayed in Fig. 5 for both experiments exactly as in Fig. 5. But here the lines connect points with identical average-of-pitches (such identity in Fig. 9 is represented by identical symbols). The connecting lines are very close to horizontal. As many as seven very different 2-line stimuli with the same average-of-pitches generate very nearly the same VPEL. Fig. 9(c) plots VPEL as a function of the average-of-pitches; the tight packing of all of the points with a common average-of-pitches (from one data point (at $\pm 30°$) to seven points (at 0°) are plotted at the same abscissa value) indicates the simplification. Most regularly for the pitched-from-vertical lines of Experiment 1, but also very clearly for the oblique (equivalent-pitch) stimulus lines of Experiment 2 then, VPEL constancy is closely approximated for stimuli with the same average-of-pitches. For such an averaging process to be involved two things are demanded: (a) bilateral symmetry for VPEL for the individual line, and (b) linearity of the VPEL-versus-pitch function for the individual line.

(a) The condition of bilateral symmetry requires identical 1-line VPELs for left and right lines with the same pitch; VPELs for mirror symmetrical lines in the frontal plane are also required to be identical. Such bilateral symmetry for the individual line holds for the empirical data as well as can be expected: it is most simply viewed in Fig. 4 and in Tables 1 and 2.

The bilateral symmetry in the processing of the 1-line stimuli is carried over into the results for the 2-line combinations; for example, the VPEL for the combination with a $-30°$ left line pitch and $-10°$ right line pitch is indistinguishable from the VPEL for the combination with a $-10°$ left line pitch and $-30°$ right line pitch. The bilateral symmetry in the results for the 2-line combinations is visible in Tables 1 and 2 which

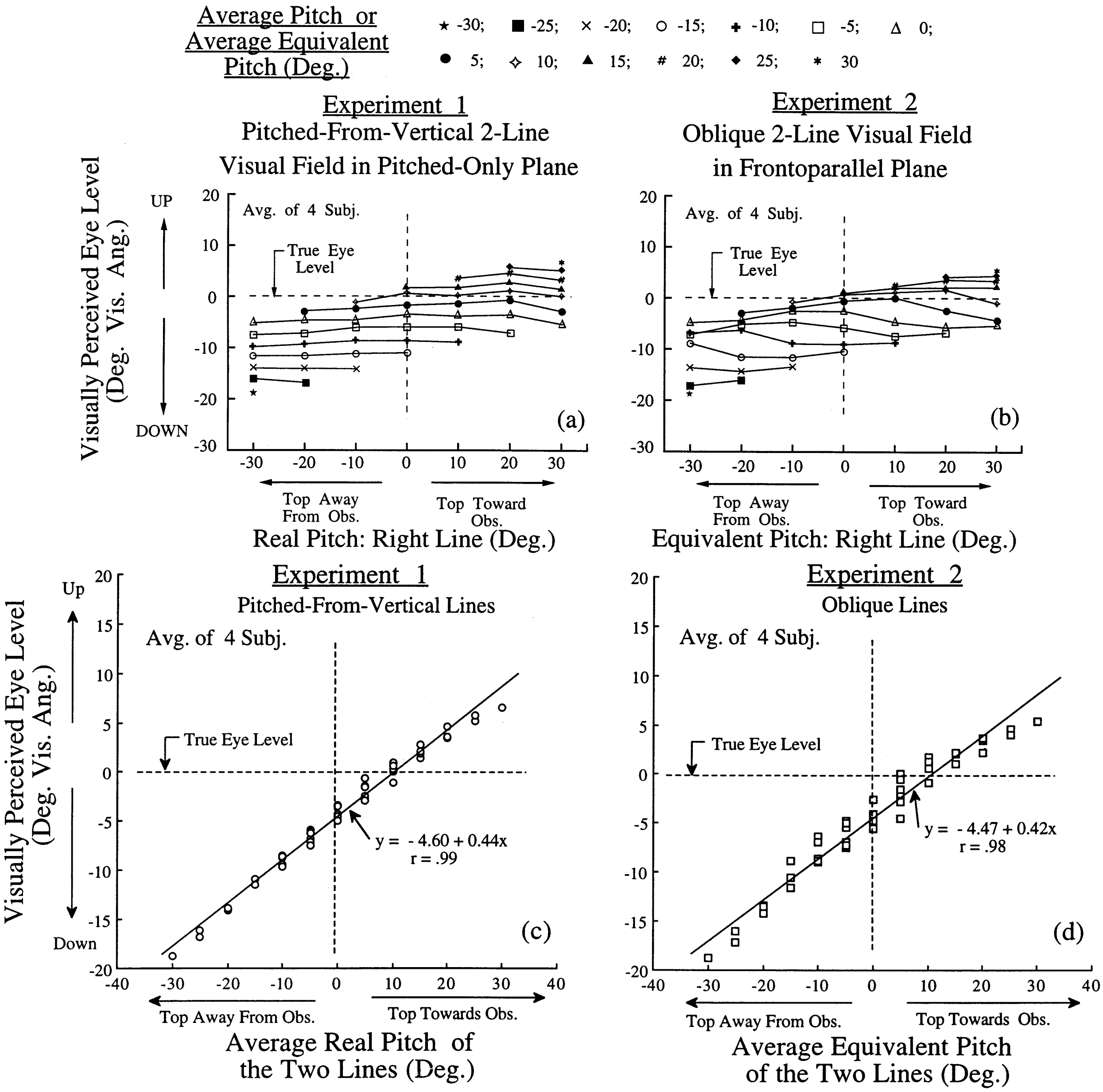

Fig. 9. The average VPELs displayed in Fig. 5(a, b) for each of the 49 conditions in each of the two experiments is reproduced identically; the ordinate and abscissa are also identical to those in Fig. 5. However, whereas, in Fig. 5, VPEL values for conditions employing the same left line are displayed with the same symbol and adjacent values with the same symbol are connected by straight lines, in the present figure a common symbol is employed for VPEL values for stimulus pairs with the same average pitch (a) or average equivalent pitch (b), and in (a) and (b) the straight lines connect adjacent points with the same symbol (average pitch equals the pitches of the left and right lines divided by two). (c, d) Plot VPEL directly against the average pitch or equivalent pitch, respectively, of the two lines in a visual field; the VPEL values are identical to those in (a) and (b), respectively, and the variation in the number of values plotted at each abscissa value correspond to the different number of cases at each pitch average (a minimum of one value at -30 and $+30°$ to a maximum of seven at 0°).

also shows the essential identity when they are stated with the right line on the abscissa and the left line as parameter or vice versa; it is even more visible in the identical appearance of graphs (not shown) with the roles of left and right lines reversed from those in Fig. 5(a, b); the symmetry is also clear under reversal of parameterized and variable lines in Fig. 6.

(b) Linearity of the VPEL-versus-pitch function for each individual line is required for the same 2-line VPEL to be obtained with two different pairs with the same average-of-pitches (e.g. a pair with $-20°$ pitch for each line as compared to pitches of $-30°$ and $-10°$ for the two lines). Linearity for the individual line is fairly well approximated in Fig. 3.

The algebraic representation of an averaging process is as follows: With θ_l and θ_r equal to the pitches of the planes containing the left and right lines, respectively, and with a and b as constants of the linear VPEL-versus-pitch relation for the 1-line stimulus, the individual influences of the left and right lines in a 2-line stimulus pair may be represented as $V(\theta_l)$ and $V(\theta_r)$ where

$$V(\theta_l) = a_l + b_l\theta_l \tag{2}$$

and

$$V(\theta_r) = a_r + b_r\theta_r \tag{3}$$

Bilateral symmetry allows the setting of $a_l = a_r = a$ and $b_l = b_r = b$. Averaging then predicts that simultaneous presentation of the two lines will be equal to $V(\theta_l, \theta_r)$ where

$$V(\theta_l, \theta_r) = [V(\theta_l) + V(\theta_r)]/2 = a + b(\theta_l + \theta_r)/2 \tag{4}$$

The averaging process of Eq. (4) matches two additional aspects of the results of Figs. 3, 5 and 9: (a) The VPEL for the 2-line stimulus in Eq. (4) possesses the same intercept as does each of the 1-line stimuli—a in Eq. (4) equals a_l and a_r in Eqs. (2) and (3); (b) $V(\theta_l, \theta_r)$ in Eq. (4) equals a linear function of the average of the two pitches regardless of how the sum of the two pitches is distributed between the two lines; thus, Eq. (4) produces an invariant VPEL for a constant algebraic pitch sum (or equivalent pitch sum). Both (a) and (b) hold fairly well in Fig. 4; we deal with the deviations in Fig. 3(a, c) in the next section. The averaging process also predicts that slopes of the VPEL-versus-pitch functions plotted as in Figs. 4 and 5 with one of the lines as variable and the other as parameter should be equal to 1/2 of the slope of the function that results when the data points for the parallel 2-line stimulus only are connected. This prediction holds exactly where the points for the parallel pairs are connected by the solid diagonal line in Fig. 5: 0.44 for the best-fitting slope for the parallel pairs versus 0.22 for the average of the seven parameterized plots in Fig. 6 for real pitch, 0.42 versus 0.20—for equivalent pitch.

6.2.2. Bilateral summation: a departure from averaging

It is of considerable interest to juxtapose an averaging process with the fact that the slope of the VPEL-versus-pitch function for the parallel, 2-line, pitched-from-vertical stimulus is greater than the slopes of the 1-line functions (Fig. 3(a, c)) (Matin and Li, 1994a,b). The fact that the slope for the parallel 2-line stimulus is larger than the slope of the 1-line stimulus implies a summation of the influences from the two lines: when a second parallel line is added VPEL departs farther from the dark value than does the VPEL for the single line. But simple averaging from Eq. (4) for a parallel line pair predicts equality between the 1-line and 2-line results, that is: $V(\theta_l, \theta_r) = V(\theta_l) = V(\theta_r)$, and the increased deviation of the empirical value of $V(\theta_l, \theta_r)$ from the dark value implies summation between the two lines above and beyond averaging. As we know from our previous work with parallel line pairs of various lengths (Matin and Li, 1994b), such summation, although considerable for short lines, is expected to be of small magnitude for the long stimuli employed here because the 64°-long lines in the present experiment lie near the asymptote of the negatively accelerating exponential function that governs the growth of VPEL with total line length (Matin and Li, 1994b). Some part of the basis for the increase of the VPEL-versus-pitch slope for the 2-line stimulus also lies in the fact that bilateral summation is greater than summation between segments of a line within one half of the visual field. Thus, for a given total length, VPEL for a 2-line stimulus is greater for the bilaterally symmetric pair than for the two lines combined as a coextensive single line (Matin and Li, 1994b). The actual differences between 1-line and bilaterally-symmetric 2-line VPELs in the present experiments are closely comparable to our earlier results.

However, when the entire set of results for parallel and nonparallel lines in Figs. 5 and 9 is viewed as a whole, no special property appears for the data points for the parallel-line pairs: although the summation within the parallel line pairs is clear in Fig. 4 from their increased slopes as it is in our previous work, in Figs. 5 and 9 those data points fit the straight line VPEL-versus-pitch functions as well as do any of the points for the nonparallel line pairs. Further, the doubling of slope for the parallel line pairs alone shown in the dark solid line in Fig. 5 relative to the slopes for the nonparallel-line functions is expected from simple averaging with or without summation (given linearity and bilateral symmetry, as noted above). If summation is a property of combinations between parallel lines but not by nonparallel line combinations the results for the topforward parallel line pairs should lie above the best fit straight lines in Fig. 5 and the results with topbackward parallel line pairs should lie below the best fit straight lines. But there is no indication of such deviations; systematic deviations for the parallel pairs are not visible in Fig. 9 either. This apparent lack of uniqueness for parallel line pairs might be thought to be a consequence of the fact that the magnitude of summation for the long lines is too small to be visible in Figs. 5 and 9. But the results on this point are too clear and consistent for experimental variability to be entertained as a likely explanation.

Thus, we are led to infer that the failure of the results for the parallel line pairs to deviate from the straight line fits in Figs. 5 and 9 indicates that the summation process does not distinguish between parallel and nonparallel line pairs but operates for all pairs. This inference can be examined further by comparing the VPEL for the 2-line combinations to the average of the VPELs for the individual line. The fact that the slope is greater than 1 in Fig. 10 for real pitch (1.22) and for equivalent pitch (1.16) supports the inference of summation for all combinations. Although in Fig. 10(a) and somewhat more in Fig. 10(b) there is an offset of the data from the slope-of-1 line that brings the topbackward (or equivalent topbackward) VPELs closer to the slope-of-1 line than those for topforward pitch, this does not obscure the trend indicating summation from the greater-than-1.00 slope: Thus the paired values in Fig. 10(a) lie above the diagonal for positive average-of-pitches (topforward) and below the diagonal for the larger negative pitch averages (topbackward), indicating that VPEL for the 2-line combination is consistently larger than the average of the VPELs for the two individual lines. Again, we conclude from this that summation above and beyond averaging is a process that is not unique to parallel lines, but holds between lines at all combinations of orientations as well.

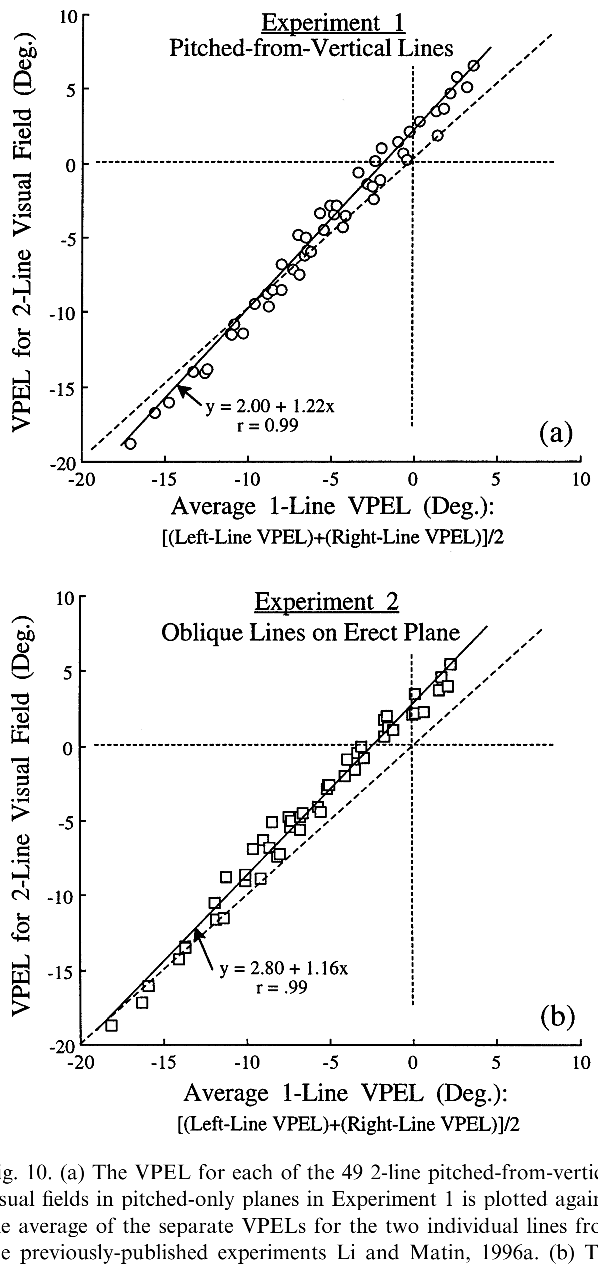

Fig. 10. (a) The VPEL for each of the 49 2-line pitched-from-vertical visual fields in pitched-only planes in Experiment 1 is plotted against the average of the separate VPELs for the two individual lines from the previously-published experiments Li and Matin, 1996a. (b) The VPEL for each of the 49 oblique 2-line stimuli in the frontoparallel plane in Experiment 2 is plotted against the average of the separate VPELs for the two individual oblique lines from the previously-published experiments. The best fits are shown as the solid lines; the dashed diagonal line is the slope-of-1.00 line.

6.2.3. Opponency and averaging

Opponency has been inferred for mechanisms controlling perceptual dimensions for which a psychological neutral point can be designated and where an appropriate adjustment of the relative strengths of two opposing processes can be effected so that the neutral point is reached; when the strengths of the two processes are unbalanced by either stimulation or adaptation so that the resultant lies to one side of the neutral point perception possesses one quality, with the resultant on the other side perception possesses a different quality. The egocentric perception of elevation is such a mechanism with VPEL as a neutral point and with ‘above eye level’ and ‘below eye level’ as the opposed perceptual qualities on opposite sides of the norm VPEL. Opponency is manifested in the present results by the approximation of the elevation of VPEL for the 2-line stimulus to the value that would be obtained by a line whose pitch equals the average-of-pitches of the two lines.

Fig. 11 displays representations of the opponent aspects of the present results. The pitches of the right and left lines are linearly ordered along the left and right ordinates in each of the panels. The elevation of VPEL is located on the ordinate representing physical elevation (center vertical line) by the intersection on that ordinate with a straight line extending between the points corresponding to the pitches of the two lines on the left-line and right-line pitch ordinates. Thus, straight lines referring to different pitch pairs that intersect the center ordinate at the same point indicate the same physical elevation for VPEL since they imply the same average-of-pitches regardless of the individual values of the two constituents: Fig. 11(a) shows two different pairs of pitches with the same average-of-pitches and the same VPEL elevation. Fig. 11(b) displays the VPEL elevation resulting from stimulation by a left line at $-30°$ combined with a right line at $+10°$; the resulting VPEL is lower than the value in Fig. 11(a) and is at an elevation that would also be produced by two lines both of which are pitched at $-10°$, the average of the pitches of the two lines in the stimulus. Fig. 11(c) shows the elevation of VPEL resulting from two bilaterally symmetric lines at the same pitch (parallel, 2-line, pitched-from-vertical stimulus or lines of equivalent pitch).

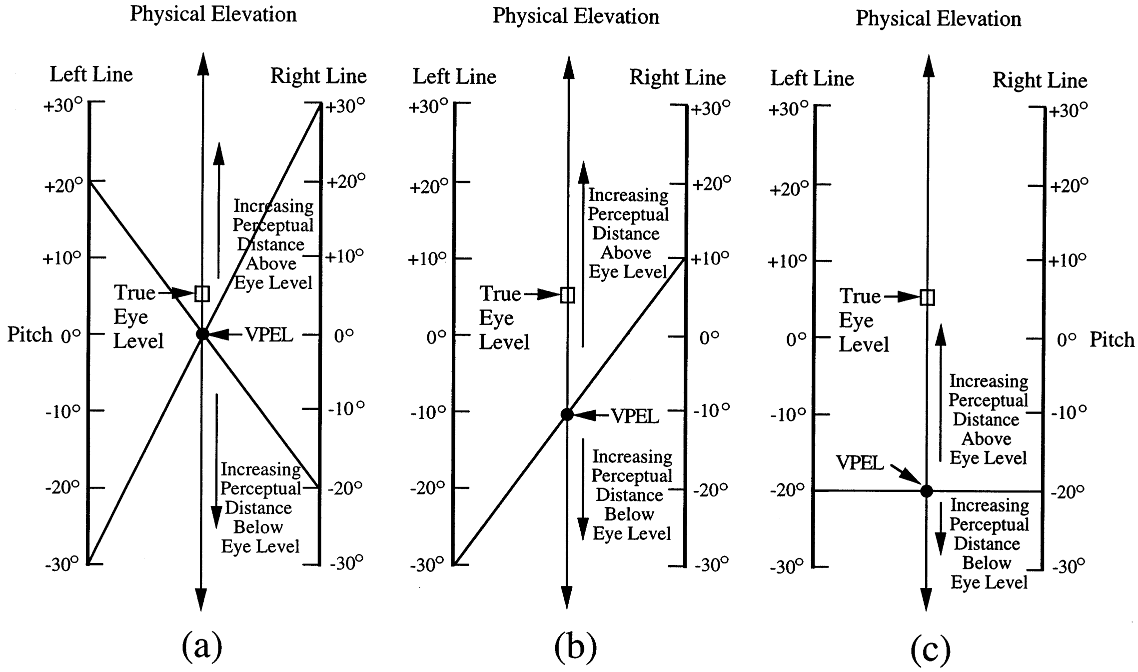

Fig. 11. Each panel displays the elevation of visually perceived eye level (VPEL), the neutral-point norm, along the center scale of physical elevation as determined by the average of the pitches of two stimulus lines; the pitches of the two stimulus lines are the values at the endpoints on the two pitch ordinates of the connecting straight line shown; in each case VPEL intersects the center ordinate at the same height as does the average of the pitches of the two stimulus lines. For two lines with pitches of equal magnitude and opposite deviations from the erect orientation, as in each of the two cases displayed in (a), the physical elevation corresponding to VPEL is slightly below true eye level (TEL). With an average-of-pitches less than zero, as in (b), VPEL is displaced downward, with a corresponding downward displacement of the entire scale of perceived elevation. With two lines of equal pitch VPEL is shown in (c) as equal to the value that would be measured with one of the two lines alone. The opponency in the perceptual dimension is indicated by the two different perceptual qualities on the two sides of VPEL: 'above eye level' and 'below eye level'; increasing distances in the two directions along the physical dimension of elevation correspond to increases in these two opposing perceptual qualities. This figure, designed to highlight the opponency involved in the process controlling the visual influence on visually perceived elevation leaves out entirely the representation of summation in the present results.

All points above the physical elevation corresponding to VPEL are perceived as above eye level and all points below the physical elevation corresponding to VPEL are perceived as below eye level, with increasing physical distances above and below VPEL corresponding to increasing perceptual distances. This aspect of Fig. 11 conforms to the measurement of linearly increasing perceptual distance from perceived eye level with increasing physical distance both above and below VPEL (Matin and Li, 1995a; Robison, Li and Matin, 1995). It also provides the basis for interpreting our earlier observations in the well-illuminated pitchroom: a person standing against the pitched surface inside the pitchroom is perceived as systematically larger than normal with increases in topbackward pitch and systematically smaller with increases in topforward pitch (Matin and Fox, 1989; Stoper and Bautista, 1991).

The opposed perceptual qualities 'above eye level' and 'below eye level' extend in opposite directions from VPEL. Since VPEL is at different physical elevations in the three panels; the entire scale of perceived elevation is shifted so as to be recentered at the physical elevation corresponding to VPEL in each panel. The two pitches in each of the pairs in Fig. 11(a) are of equal magnitude but opposite directions, and thus yield an average-of-pitches at zero (erect). However, we have shown the elevation of VPEL in these cases as falling a short distance below true eye level (TEL) by displacing the elevation dimension in the figure (and so TEL) slightly above the horizontal line that connects the locations representing 0° pitch on the two outside ordinates; this places the diagonal intersections in the same position relative to TEL as in Fig. 3 and was done on the assumption, described above, that the small displacement of VPEL from TEL represents the influence of the body-referenced mechanism in combination with zero visual pitch.

6.3. Some considerations relating to the neurophysiology of VPEL

The marked sensitivity of VPEL to line orientation points to primary visual cortex as a first major step in the organization of the visual influence. However, considerable processing is required between the initial orientation-selective visual response to lines and the combining of the visual influence with influences from the body-referenced mechanism prior to the generation of the spatiotopic perception of elevation. Although there is solid evidence for the existence of extraretinal inputs to the entrance to cerebral cortex employed by vision, V1, and evidence that signals leaving V1 are other than retinotopic for at least some spatial dimensions (see Matin and Li, 1992a, for references), if we make the more conventional assumption of a retinotopic output from V1, it would be more efficient for (a) the combination of influences from the different orientations to take place close to V1 by employing a single neuronal signal to carry the net visual influence to a region where it is combined with the influence from the body-referenced mechanism than (b) to send a neuronal signal regarding each visual orientation over a distance and combine the influences from the separate sources at the distant region.

The present results do not provide new information regarding the neuroanatomical locus for determination of VPEL. But they do supply guidance regarding the mechanism by which influences from different line orientations combine. The guidance stems from five main features of the results which have led to some additional experiments and to a model that accounts for the visual influence on VPEL. The additional experiments will be described in two subsequent articles and the model in a fourth (in preparation; an abbreviated presentation of the model is given in Matin and Li, 1997a,b). The five main aspects of the results that provide defining characteristics for the model are: the three that have been extracted from the present results and whose presence has been described in the previous three sections (averaging, summation, and opponency), the central role of orientation-sensitivity for the VPEL response, and the bilateral symmetry of orientation sensitivity. It is important to note that, as described above, bilaterally symmetric line orientations within an erect frontoparallel plane that arise from the two halves of the visual field generate identical influences on VPEL whereas parallel orientations from bilaterally-located line stimuli within such a plane generate opposite influences. This arrangement for VPEL is the opposite of the rule for the visual influence on the perception of the vertical in the frontoparallel plane (VPV) (Matin and Li, 1994c), and also opposite to the one that appears to guide grouping operations in pattern perception; in both of the latter cases parallel lines on opposite halves of the visual field generate identical influences and bilaterally symmetric orientations generate opposite influences.

A sixth significant defining characteristic for the theoretical treatment of the visual influence on VPEL stems from subsequent measurements (Li and Matin, 1996b) which show that two short lines with any combination of orientations combine by linearly additive summation of their separate influences. The model generates summation for small simultaneous neural inputs to a single neural unit and averaging for large neural inputs; this is obtained with a combination of inputs that shifts the combined response from summation for short lines to nearaveraging for long lines, and is accomplished by means of a neural network in which conductance change at a synapse on to a combining neuron grows linearly with line length and for which the current signal to the axon of the combining neuron varies linearly with line orientation. The circuit also yields an interpretation of the results of experiments with three short lines, experiments which suggest the conclusion that, although the properties of summation are essentially indistinguishable for parallel and nonparallel lines, the outputs of coextensive and parallel lines are combined prior to the combination of lines differing in orientation (Li and Matin, 1997). The model requires only two orientation-selective units operating as an opponent pair for a thorough interpretation of the visual influence on VPEL.

Here we only briefly comment on one aspect of the present results that plays a prominent role in providing support to that model. This aspect is reminiscent of phenomena that played a central role in the early analysis of spatial convergence among separate input streams in the spinal cord (Sherrington, 1929): The 0.44 slope of the 2-line VPEL-versus-pitch function for the parallel line pair is only slightly greater than the 0.36 slope of the 1-line function (Fig. 3), and the 0.22 slope of the parameterized 2-line function (Figs. 4 and 5) is smaller than both of these. Thus, the addition of a second line to a 1-line stimulus does not add as much to the influence on the elevation of VPEL as does the second line presented alone. This is analogous to the result which Sherrington labeled 'spatial occlusion' and from which he inferred that the two spatially separated inputs share a common pool of responding neurons, an inference that remains quite common today for conditions in which asymptotic responding is measured in conjunction with additivity failure as in the present case. Such occlusion was presumed to result from the fact that the response in the shared segment of the pool was already at or near maximum with one of the inputs present, a view that was supported by the fact that occlusion was prominent at high intensities of stimulation but not at low intensities where nearlinear summation was the rule. Our results with individual and paired lines mirror these results. Thus, occlusion is present in the present experiments with long lines, but linear summation is the rule with short lines as we describe in our subsequent report (Matin and Li, in preparation). The fact that the characteristics of spatial interaction are so similar across such different scales, involving small groups of neurons contributing to a motor response in Sherrington's work and psychophysical measurements on perception by the whole organism here suggests that the same fundamental laws of combination may be involved and that their function at the more complex level may be inherited from the simpler level. The fact that occlusion appears to hold here for 2-line stimulation with long lines regardless of the relation between orientations of the two constituent lines also provides some basis for believing that the neural units responsible for generating the visual influence on VPEL are themselves broadly tuned for orientation. These are matters that will receive further attention in the subsequent reports.

Acknowledgements

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